

# « Development of Micro-Pattern Gaseous Detector Technologies » and the RD51 Collaboration

Maxim Titov, CEA Saclay, France



## OUTLINE of the TALK:

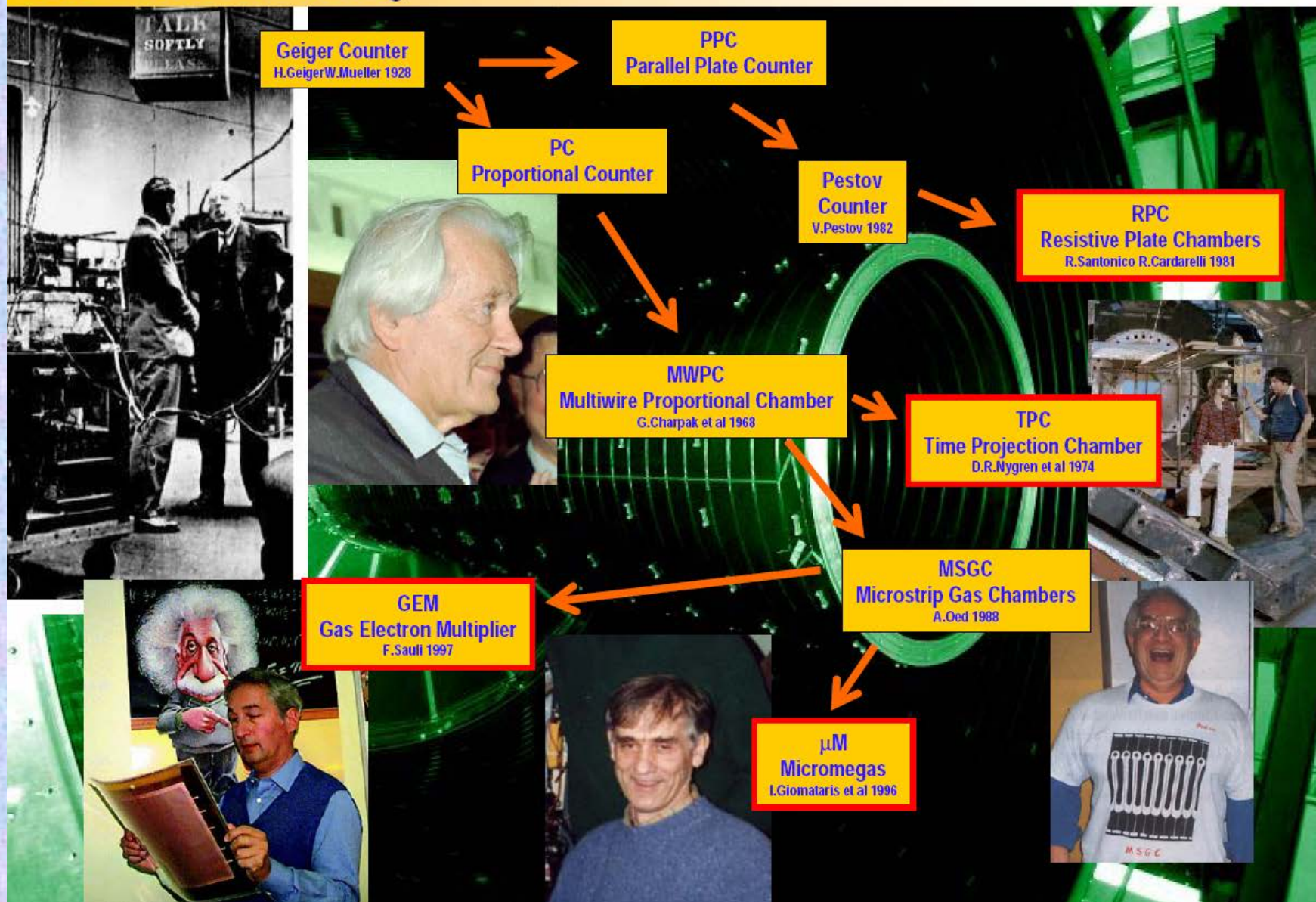
- Introduction: Major Micro-Pattern gas Detector Technologies (GEM, Micromegas, Thick GEM, InGrid, mPIC)
- Summary of the RD51 – MPGD Technology Highlights  
(Large area MPGDs - Support of HL- HLC Upgrades, R&D (quality control, long-term tests), Academia-Industry Matching Event, Software & Simulation, SRS Electronics, CERN MPGD Production Facility & Industrialization, RD51 Test Beam Facility, Training)

Joint Instrumentation Seminar, DESY/Hamburg, September 4, 2015



# History of Gaseous Detector Developments

## Gas Detector History

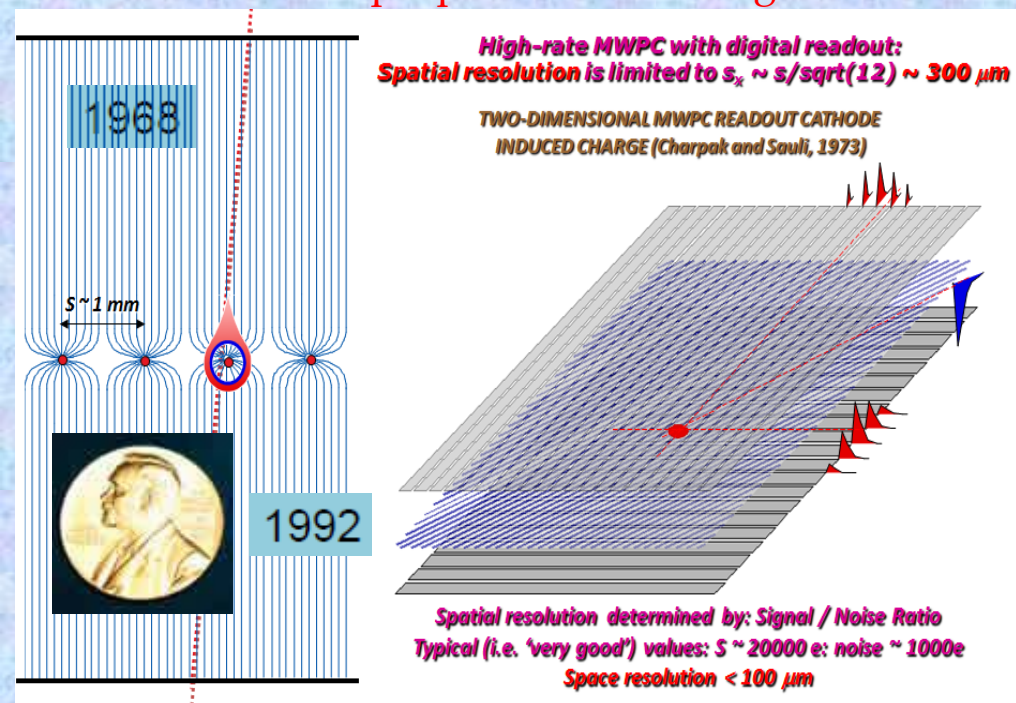




# Multi-Wire Proportional Chamber (MWPC)

Gaseous proportional tracking detectors that revolutionized High Energy Physics

With Fabio Sauli et Jean Claude Santiard  
The 1st "Large Wire Chamber" ...



The invention revolutionized  
particle detection, which  
passed from the manual  
to the electronic era.

Georges Charpak  
1924 – 2010



# Nobel Prize: W, Z - Discovery at UA1/UA2 (1983)

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

It can now be seen in the CERN  
Microcosm Exhibition

Particle trajectories in the CERN-UA1

**3D Wire Chamber**

*Discovery of W and Z bosons*

*C. Rubbia & S. Van der Meer*

Nobel Prize 1984

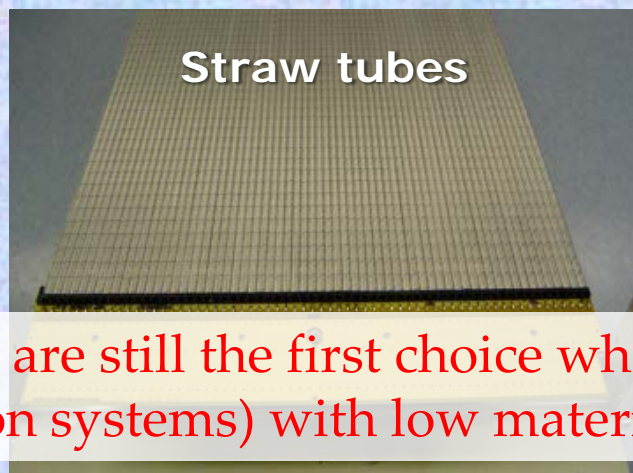


$Z \rightarrow ee$  (white tracks)



# Gaseous Detectors in LHC Experiments

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



Gaseous detectors are still the first choice whenever the large-area coverage (e.g. muon systems) with low material budget is required



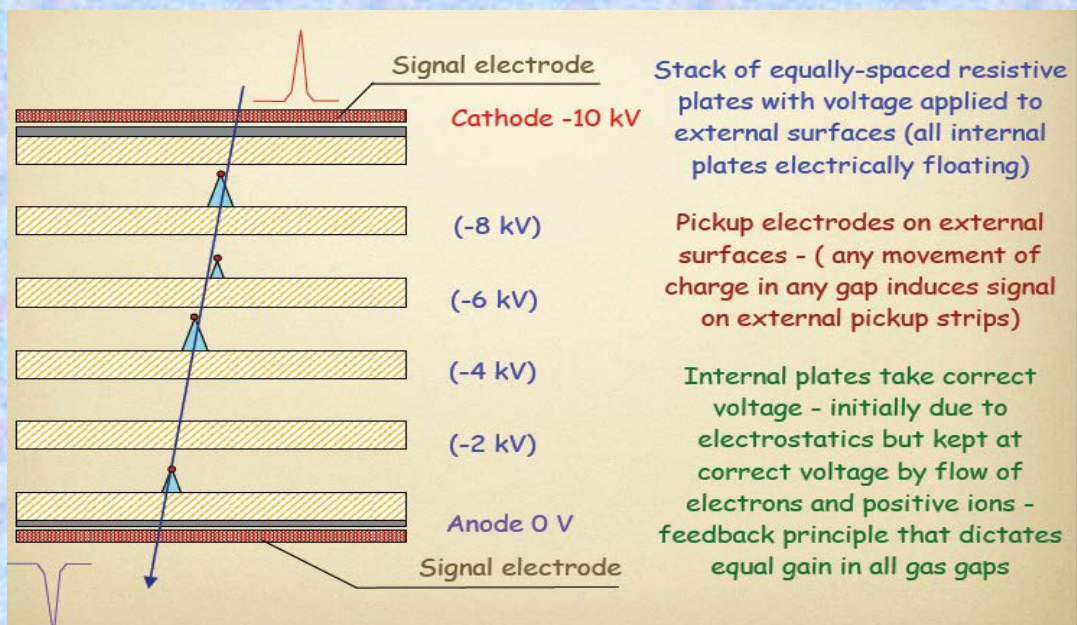
# ALICE Multi-Gap RPC: Timing Resolution

- Relevant scale in HEP:  $t \sim L(\text{m})/c \sim \text{o}(\text{ns})$

$$T_1 - T_2 = \frac{L}{c} \left( \frac{1}{\beta_1} - \frac{1}{\beta_2} \right) = \frac{L}{c} \left( \sqrt{1 + m_1^2/p^2} - \sqrt{1 + m_2^2/p^2} \right) \cong (m_1^2 - m_2^2)L / 2cp^2$$

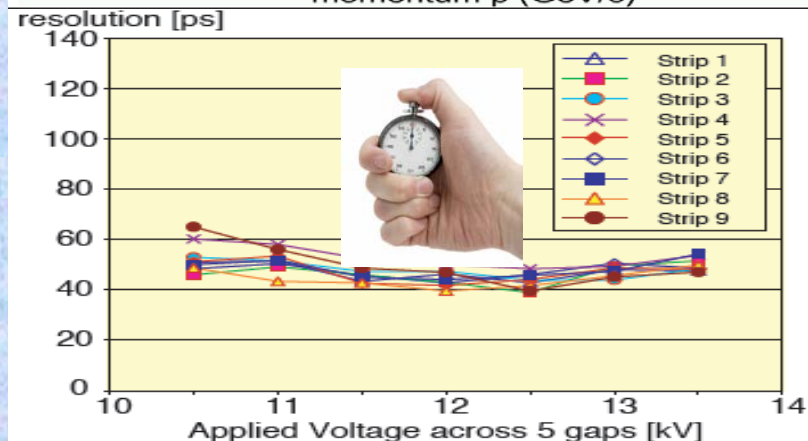
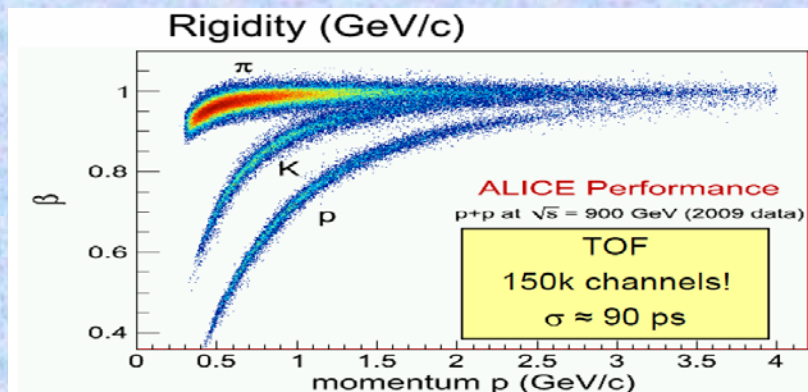
- Traditional technique:
  - Scintillator + PMT  $\sim \text{o} (100 \text{ psec})$
- Breakthrough with a spark discharge in gas
  - Pestov counter  $\rightarrow$  **ALICE MRPC**  $\sim 50 \text{ psec}$

## Multi-Gap Resistive Plate Chamber: Basic Principle



C. Williams, CERN Detector Seminar  
 "ALICE Time of Flight Detectors":

<http://indico.cern.ch/conferenceDisplay.py?confId=149006>



Technology	Time resolution
• Pestov Counter	30-50 ps
• RPC	$\sim 1\text{-}5 \text{ ns}$ (MIP)
• MultiGap RPC	$\sim 50 \text{ ps}$ (MIP)
• GEM	$\sim 1\text{-}2 \text{ ns}$ (UV) $\sim 5 \text{ ns}$ (MIP)
• Micromegas	$\sim 700 \text{ ps}$ (UV) $\sim 2\text{-}5 \text{ ns}$ (MIP)



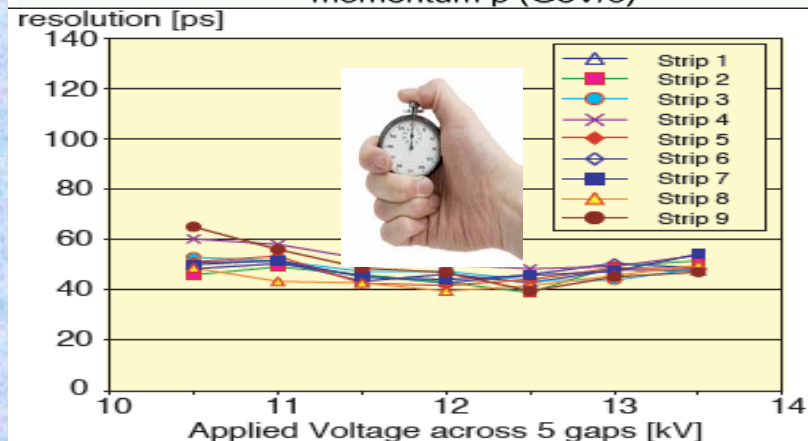
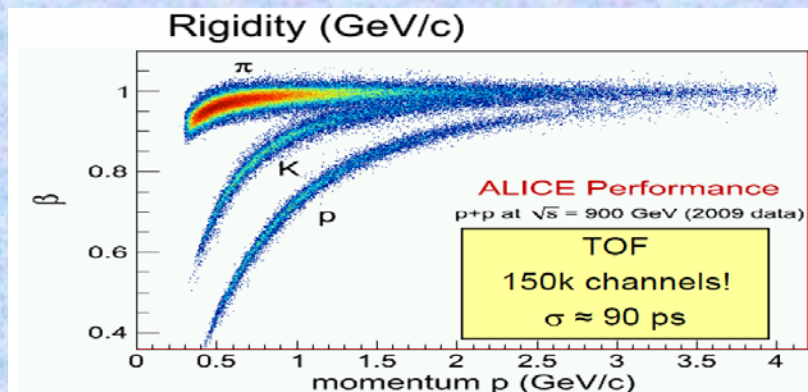
# ALICE Multi-Gap RPC: Timing Resolution

- Relevant scale in HEP:  $t \sim L(\text{m})/c \sim \text{o}(\text{ns})$

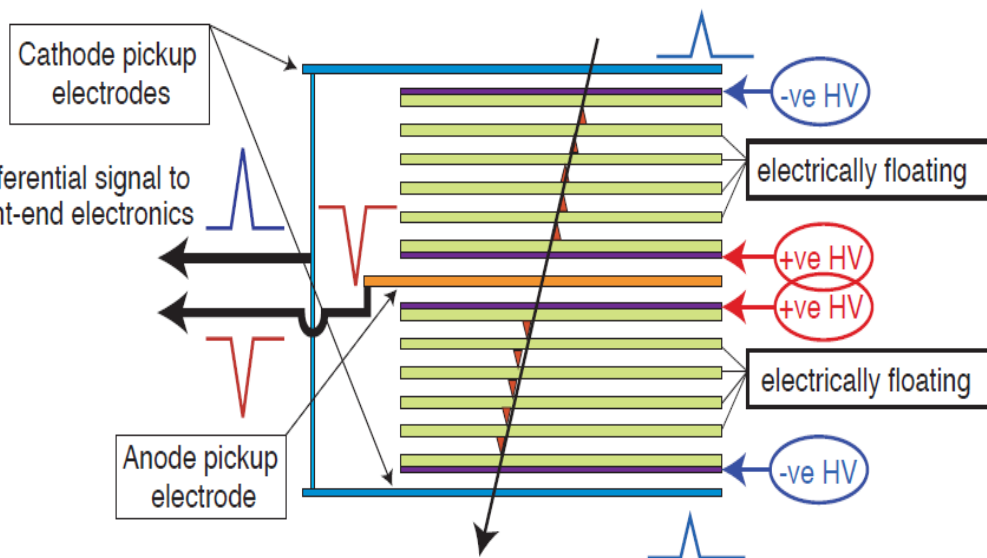
$$T_1 - T_2 = \frac{L}{c} \left( \frac{1}{\beta_1} - \frac{1}{\beta_2} \right) = \frac{L}{c} \left( \sqrt{1 + m_1^2/p^2} - \sqrt{1 + m_2^2/p^2} \right) \cong (m_1^2 - m_2^2)L / 2cp^2$$

- Traditional technique:
  - Scintillator + PMT  $\sim \text{o} (100 \text{ psec})$
- Breakthrough with a spark discharge in gas
  - Pestov counter  $\rightarrow$  **ALICE MRPC**  $\sim 50 \text{ psec}$

ALICE-TOF has 10 gaps (two stacks of 5 gas gaps);  
each gap is 250 micron wide



Technology	Time resolution
• Pestov Counter	30-50 ps
• RPC	$\sim 1\text{-}5$ ns (MIP)
• MultiGap RPC	$< 50$ ps (MIP)
• GEM	$< 1\text{-}2$ ns (UV) $\sim 5$ ns (MIP)
• Micromegas	$< 700$ ps (UV) $\sim 2\text{-}5$ ns (MIP)

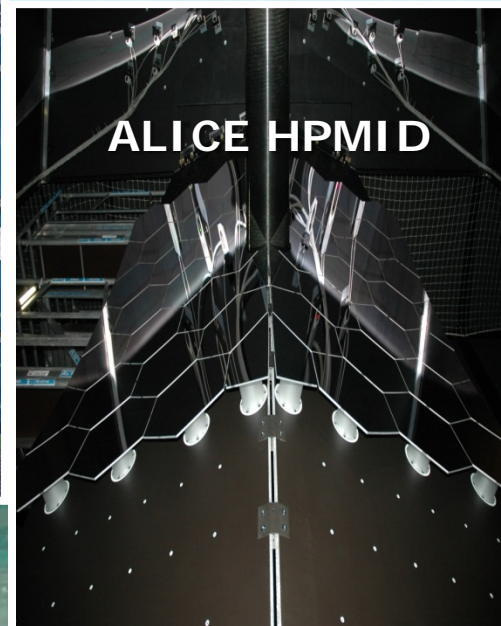
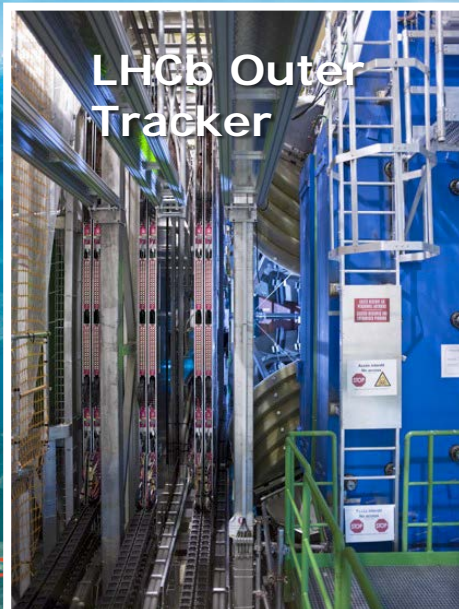


C. Williams, CERN Detector Seminar  
"ALICE Time of Flight Detectors":

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# Gaseous Detector Systems for the High-Luminosity LHC

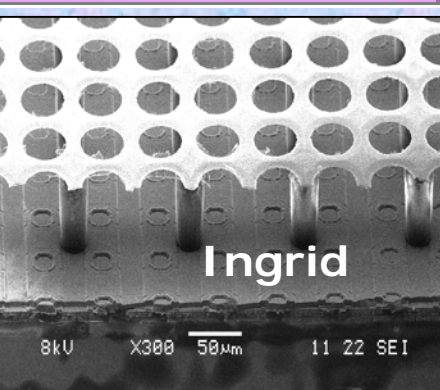
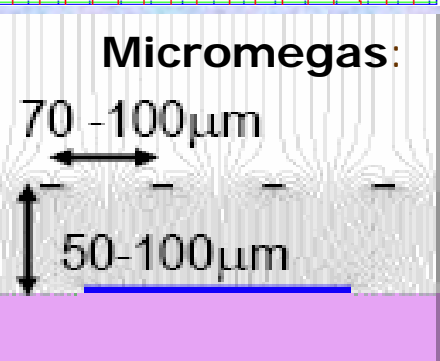
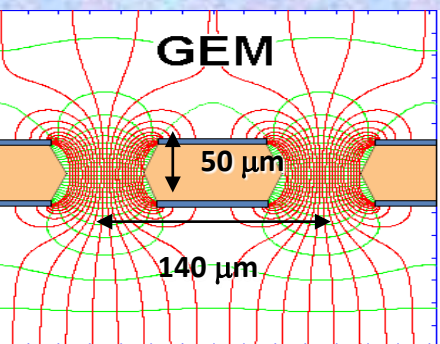
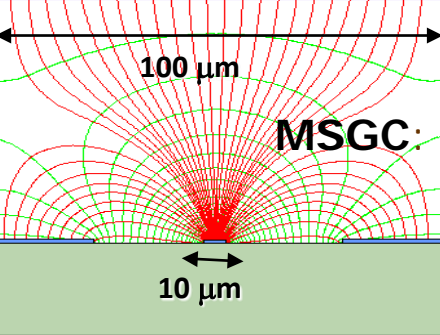


## Upgrade Options for HL-LHC:

- 1. Upgrade without changing detectors**
  - ATLAS, CMS and LHCb: Largest part of the Muon systems
  - ALICE: Replace only electronics for TRD and Muon system
  - CMS: New electronics with better trigger capabilities for DT chambers
  - R&D: Run RPCs at lower gas gain with new low noise electronics
- 2. Upgrade by scaling standard geometries**
  - ATLAS: sMDT (small Muon Drift Tubes) for BME (in LS1) and BIS (in LS2) regions
  - ATLAS: sTGCs (small-strip Thin Gap Chambers) for New Small Wheel
  - R&D: RPCs with thinner or lower resistivity electrodes
- 3. Upgrade by introducing novel gas detectors (Micro-Pattern Gas Detectors)**
  - ATLAS: MicroMegas for New Small Wheel
  - ALICE (TPC), CMS (Forward Muon system) and LHCb (Muon system): GEMs

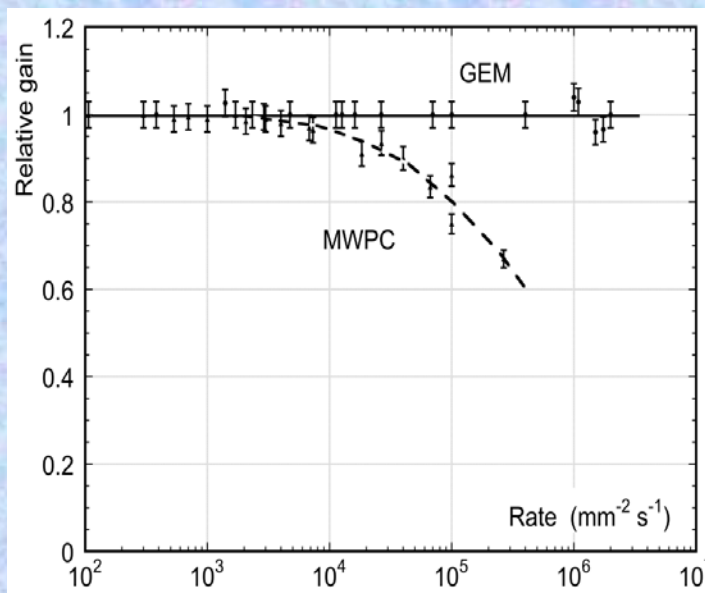






# INSTRUMENTATION FRONTIER:

## DEVELOPMENT OF MICRO-PATTERN GASEOUS DETECTOR TECHNOLOGIES



High Rates & enormous occupancy:

Silicon detectors:

Si-strips  $\rightarrow$  Pixel (2D)  $\rightarrow$  3D detectors & 3D TSV integration

Gaseous detectors:

Wire Chamber  $\rightarrow$  Wireless MPGD (2D)  $\rightarrow$  InGrid/Timepix (3D)

**Detector-Electronics Integration  $\rightarrow$  Enabled by Advanced Technologies**  
(better granularity / high precision / small amount of material)

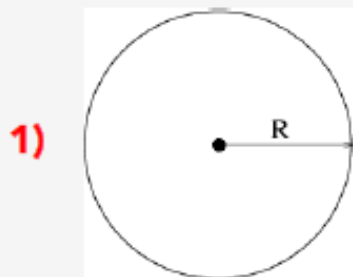
- ❖ Modern photo-lithography technology  $\rightarrow$  Micro-Pattern Gas Detectors
- ❖ Microelectronics – eg. Silicon pixels
- ❖ Bump bonding technology – low capacitance connections

Trade-offs between high-speed, power, S/N, integration, segmentation, radiation tolerance  $\rightarrow$  defined by the state-of-the-art in microelectronics

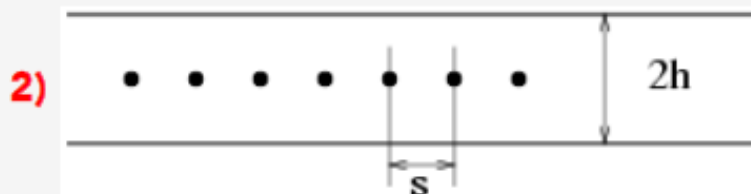
# Summary & conclusion

Christian Lippmann, 2<sup>nd</sup> ECFA High Luminosity LHC Experiments  
 Workshop, Aix-les-bains, France, October 21-23 (2014)

**Geiger- Müller (1908), 1928**  
**Drift Tube (1968)**



**G. Charpak, 1968**  
**Multi Wire Proportional Chamber**

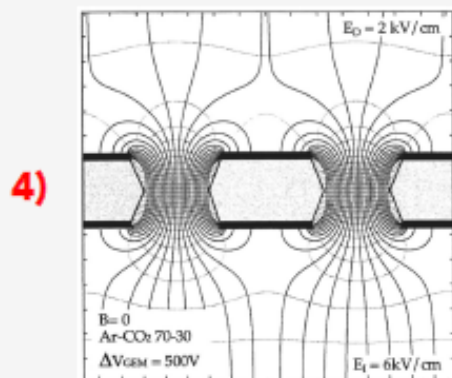


**R. Santonico, 1980**  
**Resistive Plate Chamber**

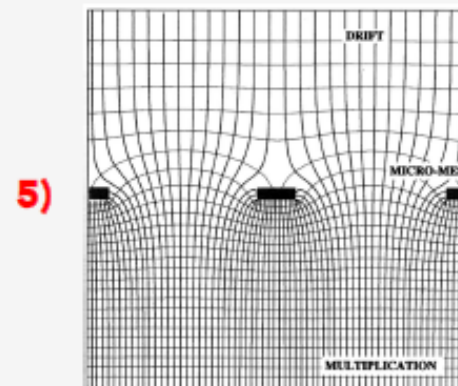


... will at HL-LHC be joined by:

**F. Sauli (1997)**  
**Gas Electron Multiplier**



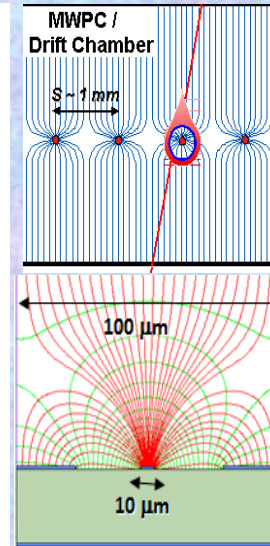
**I. Giomataris et al. (1996)**  
**Micro-mesh gaseous chamber (Micromegas)**



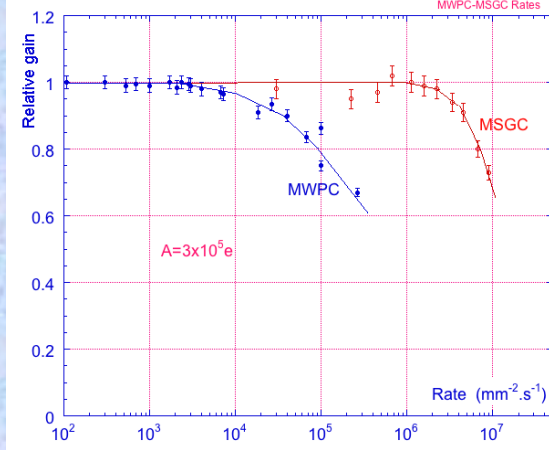


# Micro-Pattern Gaseous Detector Technologies for Future Physics Projects

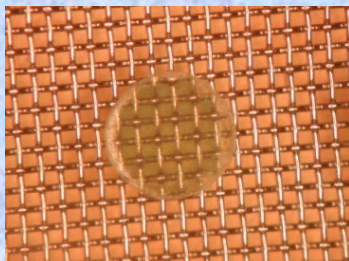
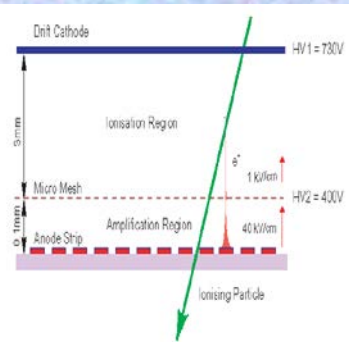
- Micromegas
- GEM
- Thick-GEM, Hole-Type and RETGEM
- MPDG with CMOS pixel ASICs ("InGrid")
- Micro-Pixel Chamber ( $\mu$ PIC)



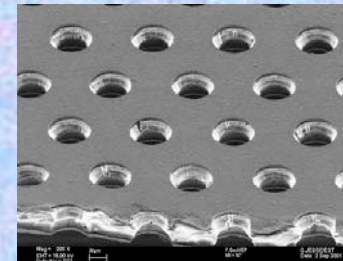
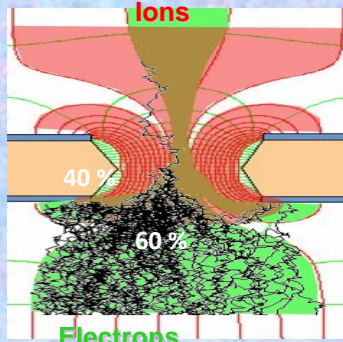
## Rate Capability: MWPC vs MSGC



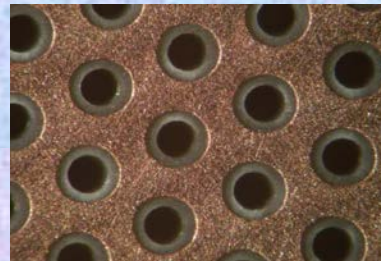
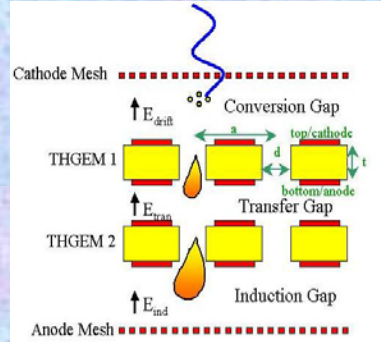
## Micromegas



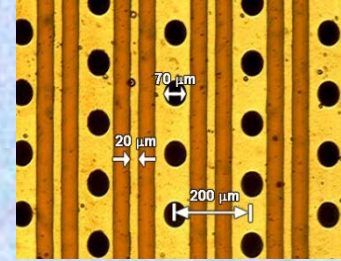
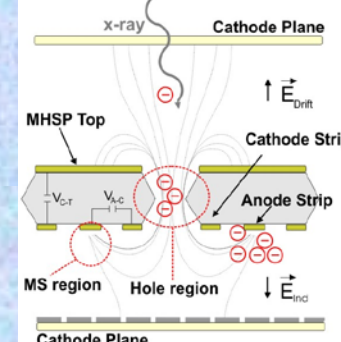
## GEM



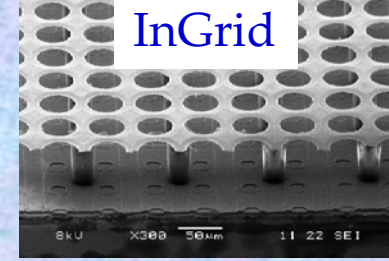
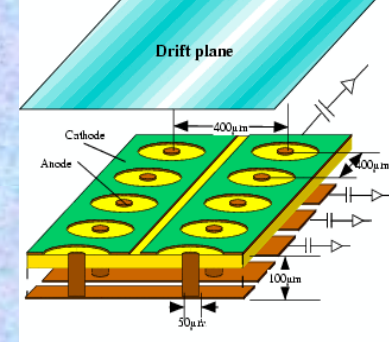
## THGEM



## MHSP



## $\mu$ PIC



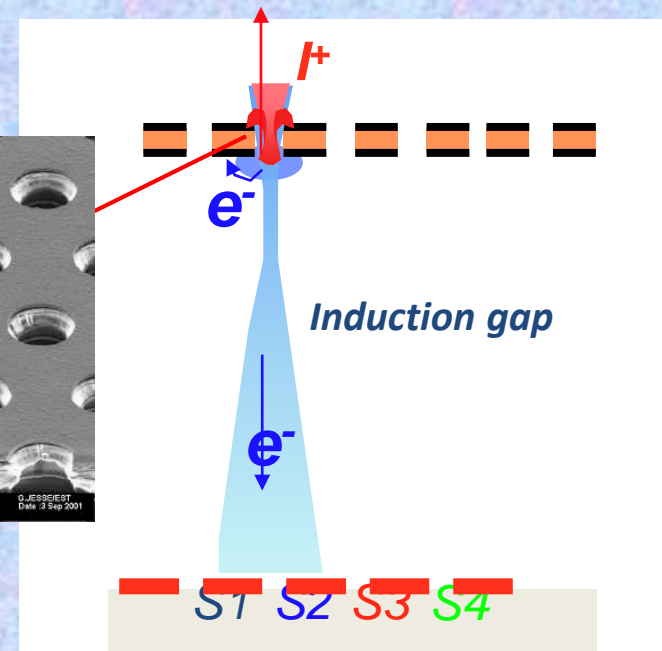
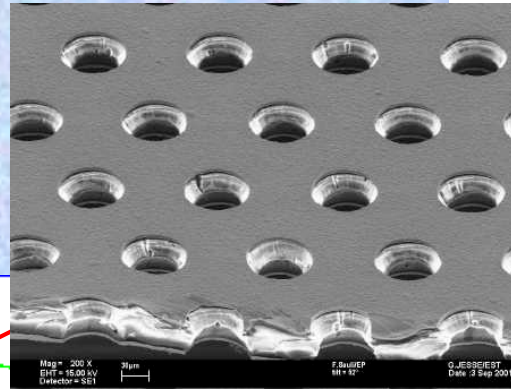
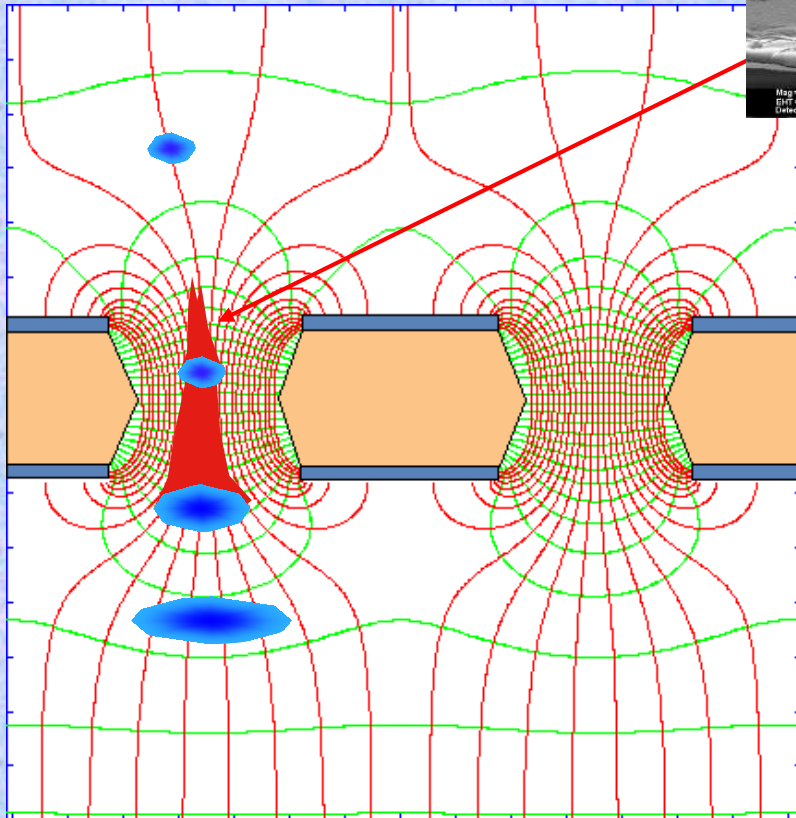
InGrid

# GEM (Gas Electron Multiplier)

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

A difference of potentials of  $\sim 500\text{V}$  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.



- 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.



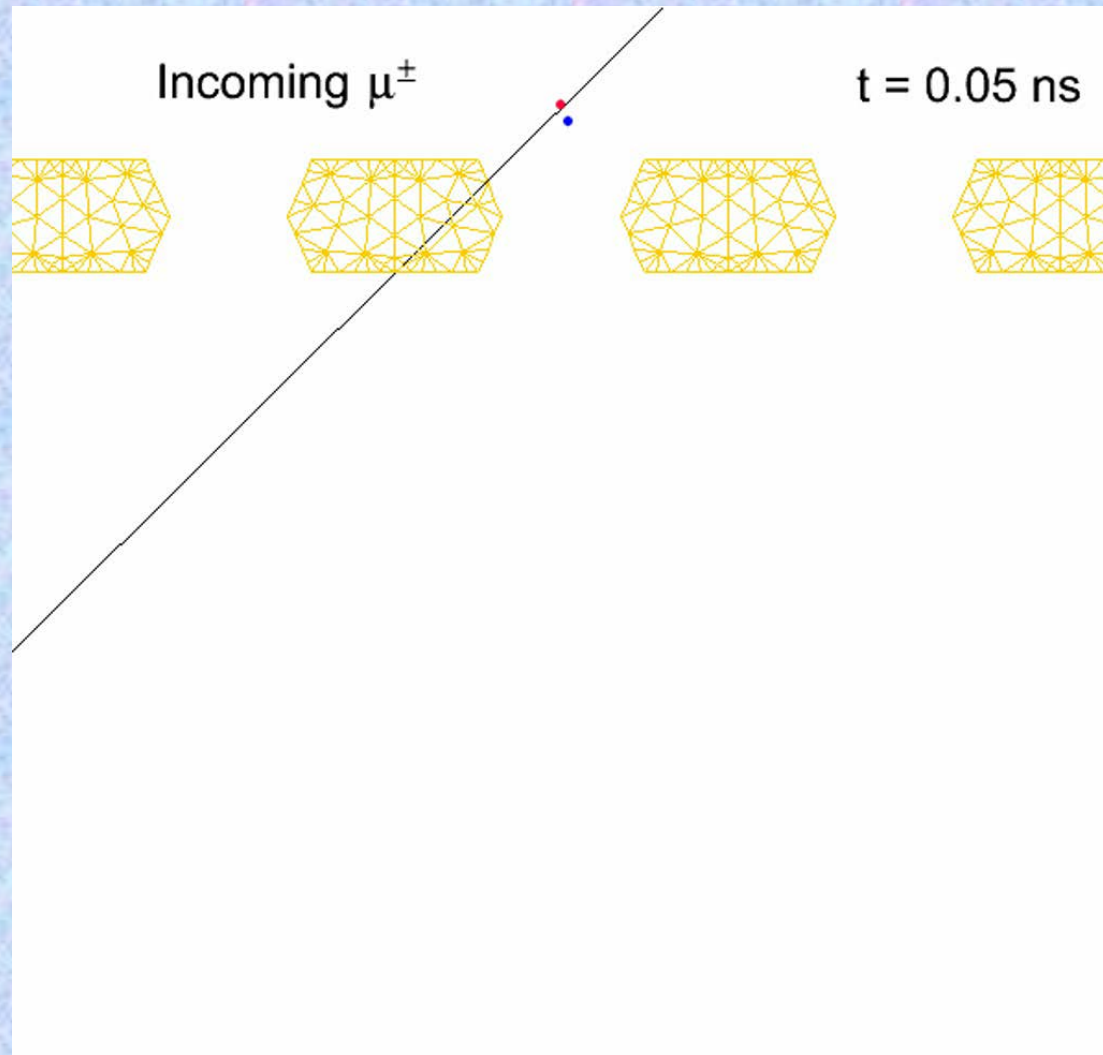
# MPGD Simulation Tools (Avalanche Simulation in GEM)



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

electrons are blue, ions are red, the  
GEM mesh is orange

- ANSYS: field model
- Magboltz 8.9.6: relevant cross sections of electron-matter interactions
- Garfield++: simulate electron avalanches



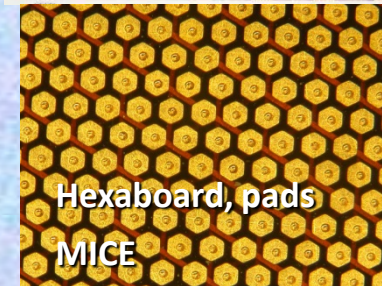
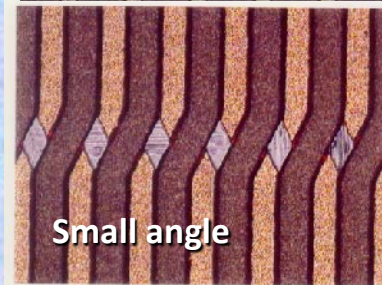
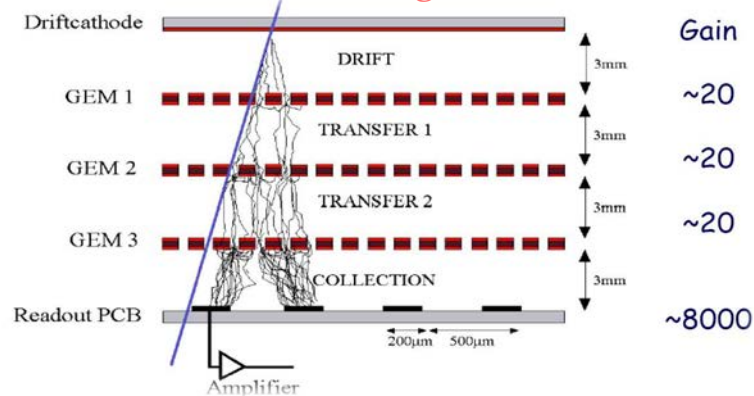
<http://cern.ch/garfieldpp/examples/gemgain>

# Gas Electron Multiplier (GEM)

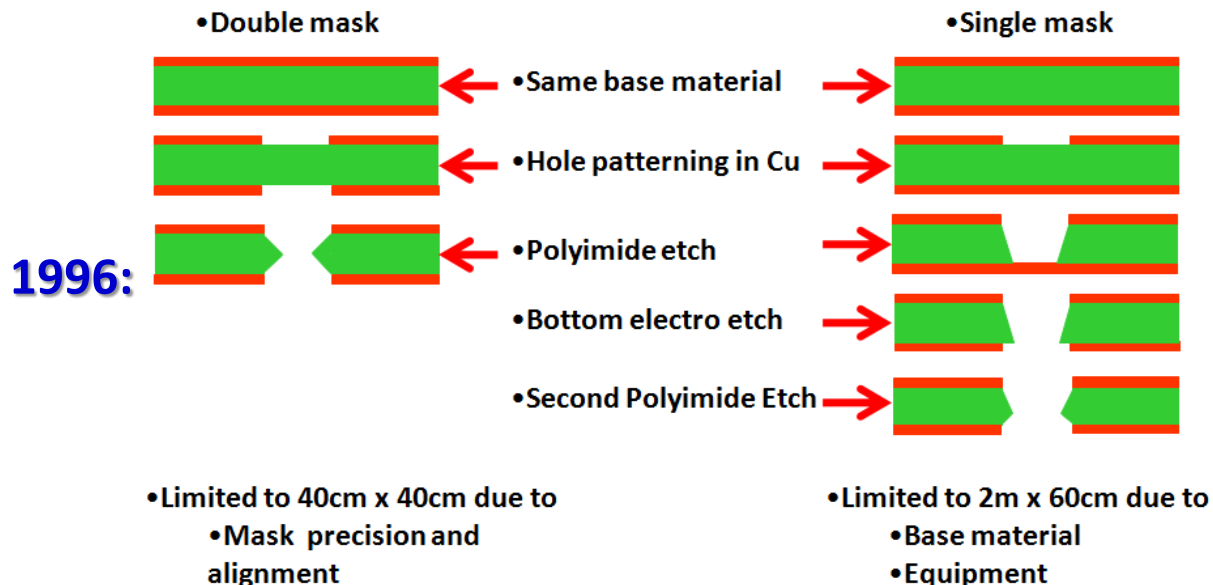
F. Sauli, NIM A386(1997) 531;  
F. Sauli, <http://www.cern.ch/GDD>



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



2009: NEW: Single mask GEM production technique →  
allow to extend GEM foils to ~ m<sup>2</sup> area



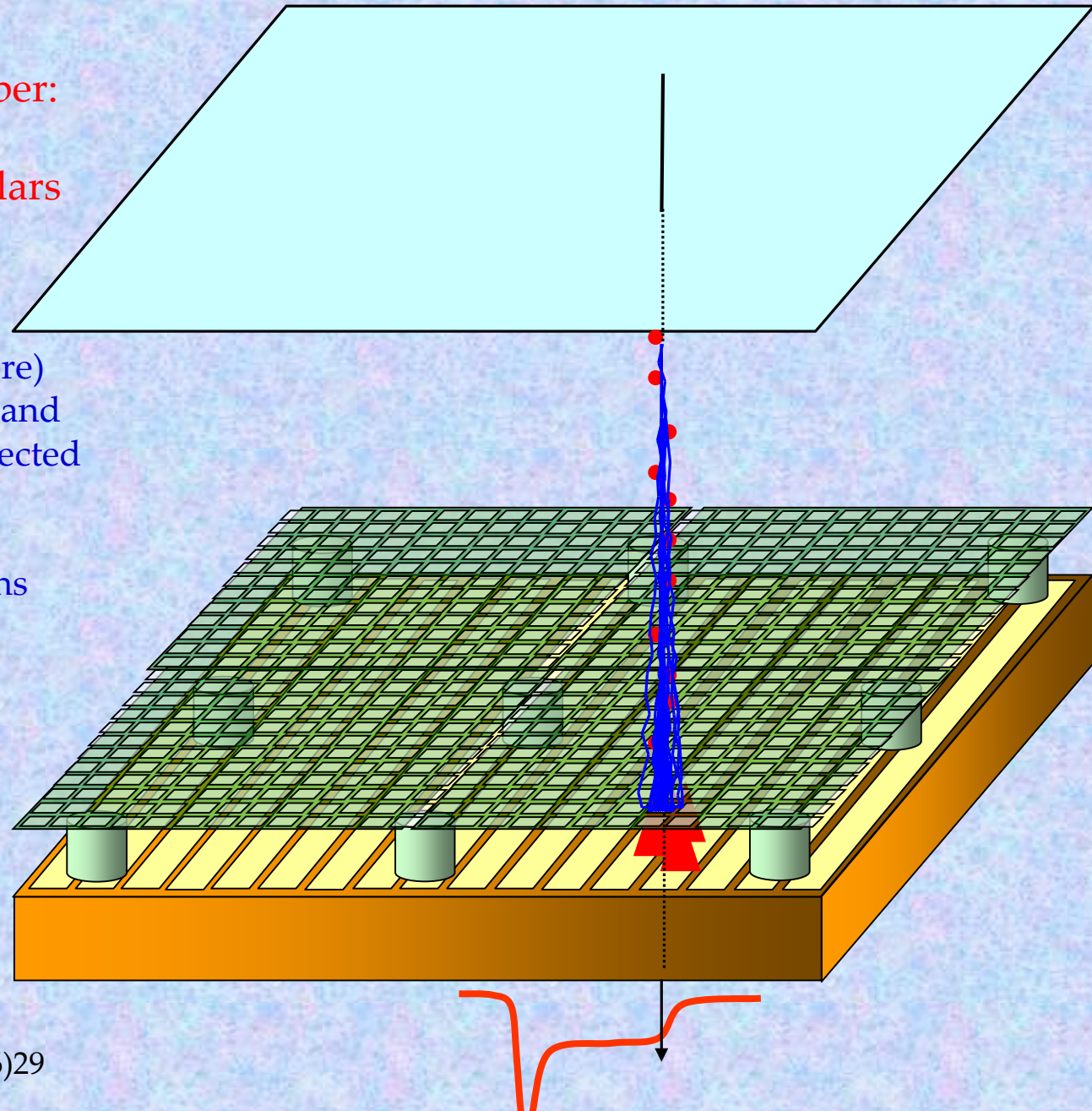
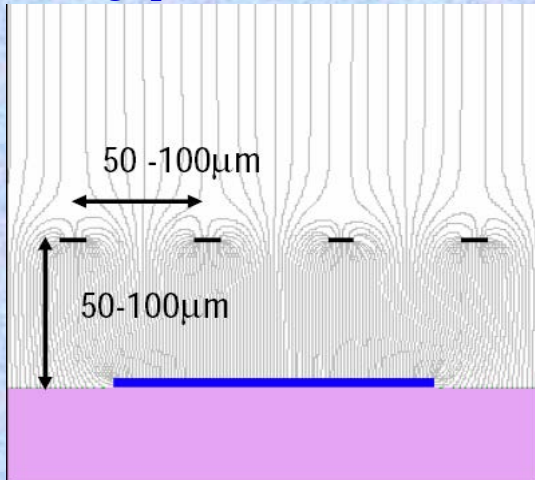


# MICro MESH Gaseous Structure (MICROME GAS)

Micromesh Gaseous Chamber:  
micromesh supported  
by 50-100  $\mu\text{m}$  insulating pillars

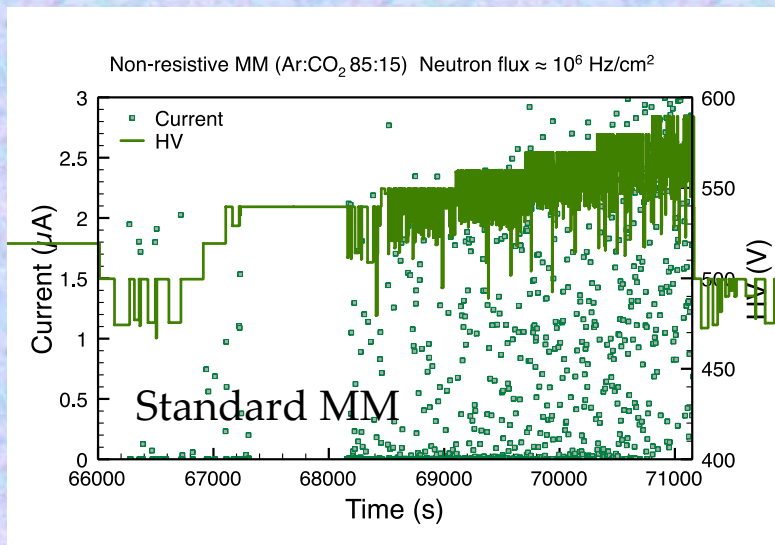
Multiplication (up to  $10^5$  or more)  
takes place between the anode and  
the mesh and the charge is collected  
on the anode (one stage)

Small gap: fast collection of ions

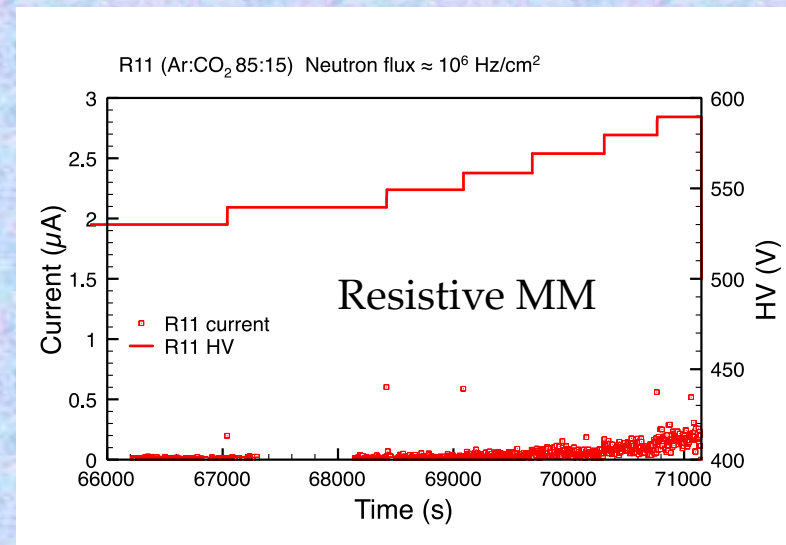


# Standard vs Resistive Micromegas Sparking

- Standard MM could not be operated in neutron beam
- HV break-down and currents > several  $\mu\text{A}$  for gains  $\sim 1000$ – $2000$



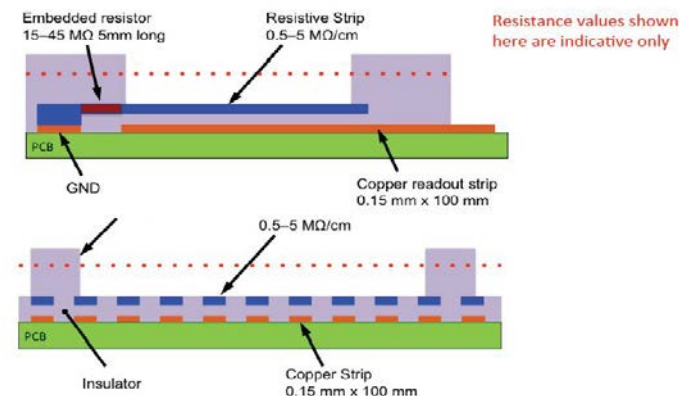
- MM with resistive strips worked perfectly well
- No HV drops, small spark currents up to gains of  $2 \times 10^4$



## Since 2010: Resistive Micromegas technology

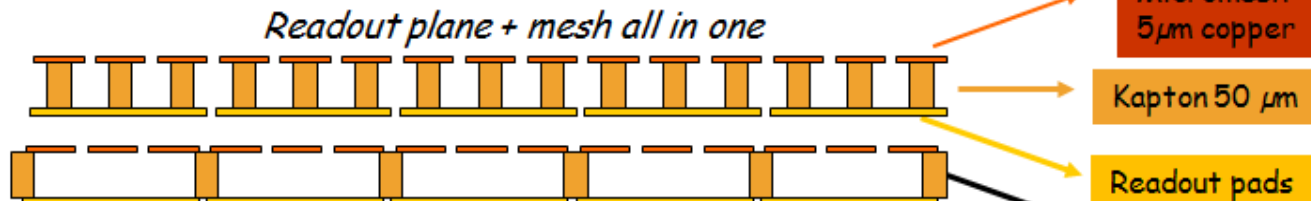
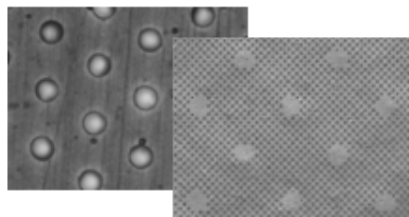
- ❖ Problem was solved by adding a layer of resistive strips above the readout strips
- ❖ Spark neutralization/suppression (sparks still occur but become inoffensive)

## The resistive-strip protection concept





# « MicroBulk » Micromegas



## Microbulk Technology

*An I. Giomataris and R. De*

The pillars are constructed by chemical processing of a kapton foil, on which the mesh and the readout plane are attached. **Mesh is a mask for the pillars!**

*Typical mesh thickness 5 µm, gap 50/25 µm*

*A microbulk has all the advantages of a bulk micromegas but with enhanced performance.*

*In addition: uniformity, clean materials, stability*

✓ **Energy resolution** (down to 10% FWHM @ 6 keV)

✓ **Low intrinsic background & better particle recognition**

✓ **Low mass detector**

✓ **Very flexible structure**

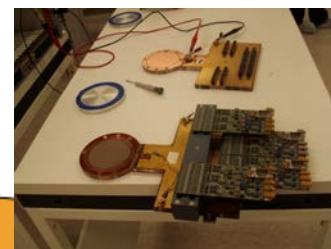
✗ Higher capacity

✗ Fabrication process complicated

✗ Fragility / mesh can not be replaced



Lower capacitance  
Under development



## Microbulk radiopurity:

→ mostly Cu & Kapton

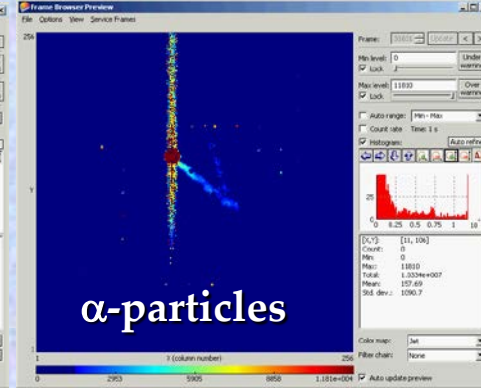
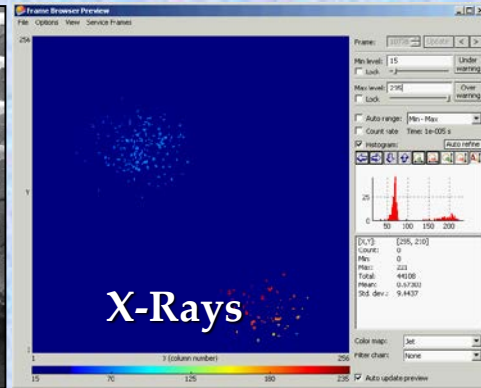
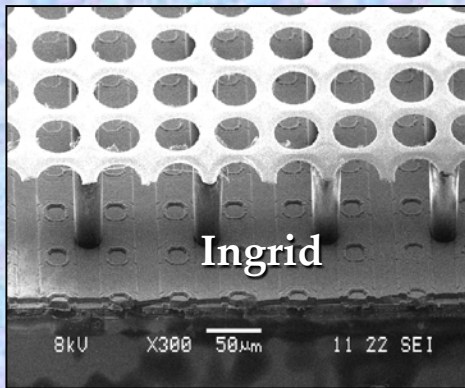
Measured with HPGe at Canfranc:

- > raw material (double clad kapton foil)
- > samples from old CAST detectors

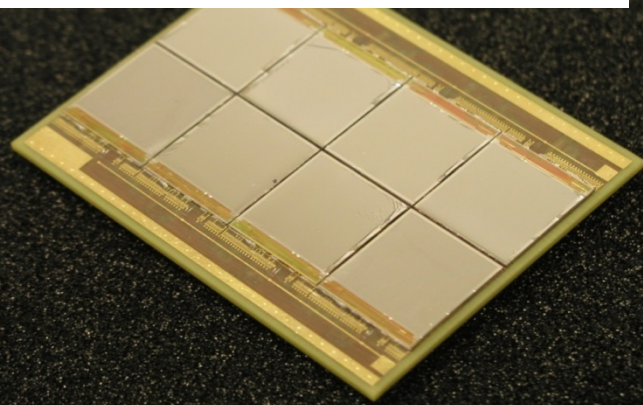
S. Cebrian et al., Astropart. Phys 34 (2011) 354-359

Results in µBq/cm <sup>2</sup>	<sup>232</sup> Th	<sup>235</sup> U	<sup>238</sup> U	<sup>40</sup> K	<sup>60</sup> Co
Microbulk	<9.3	<13.9	26.3±13.9	57.3±24.8	<3.1*
Kapton-Cu foil	<4.6*	<3.1*	<10.8	<7.7*	<1.6*
Cu-Kapton-Cu foil	<4.6*	<3.1*	<10.8	<7.7*	<1.6*

\*Level obtained from the Minimum Detectable Activity of the detector



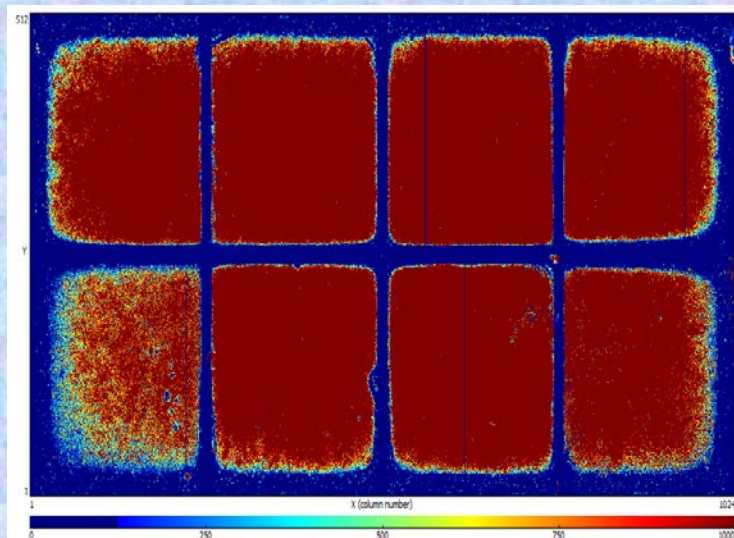
“Octopuce” (8 Timepix ASICs):



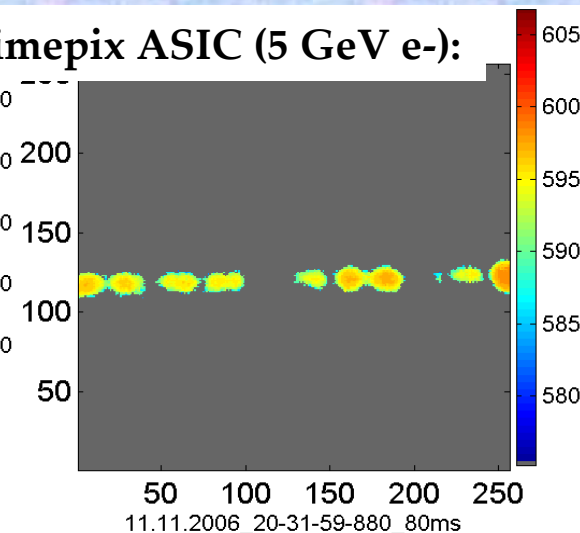
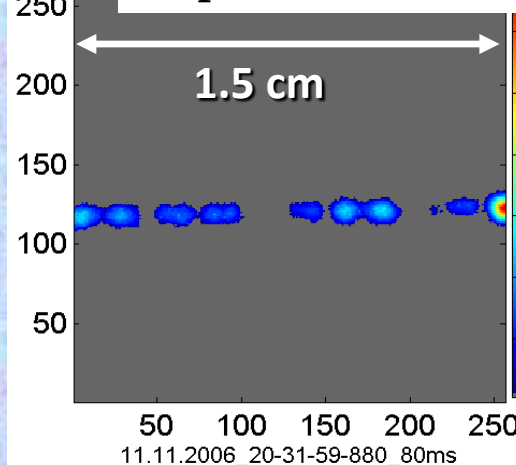
**INSTRUMENTATION FRONTIER:**

**PIXEL READOUT OF MPGDs –**

**Ultimate Gas-Silicon Detector Integration**



**Triple GEM stack + Timepix ASIC (5 GeV e<sup>-</sup>):**

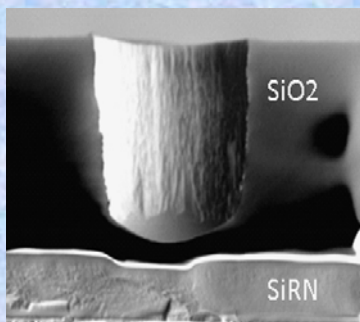
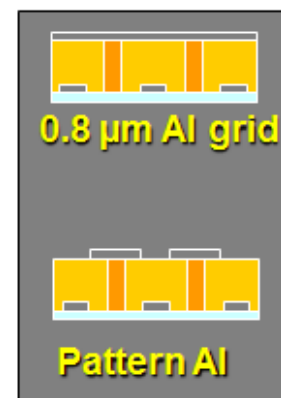
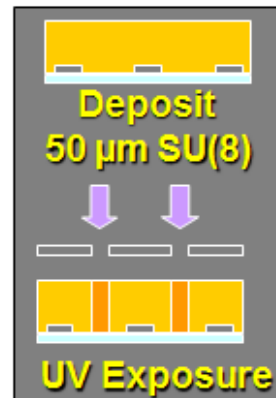
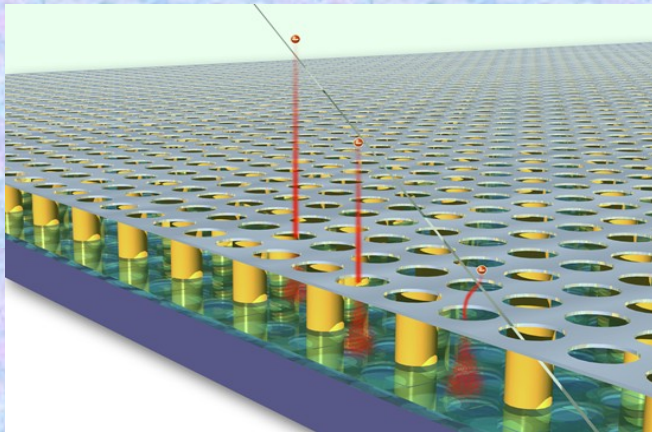




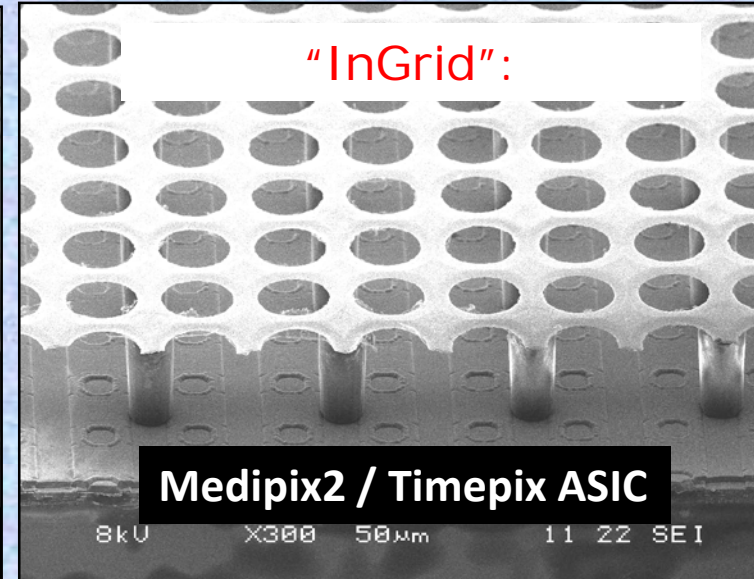
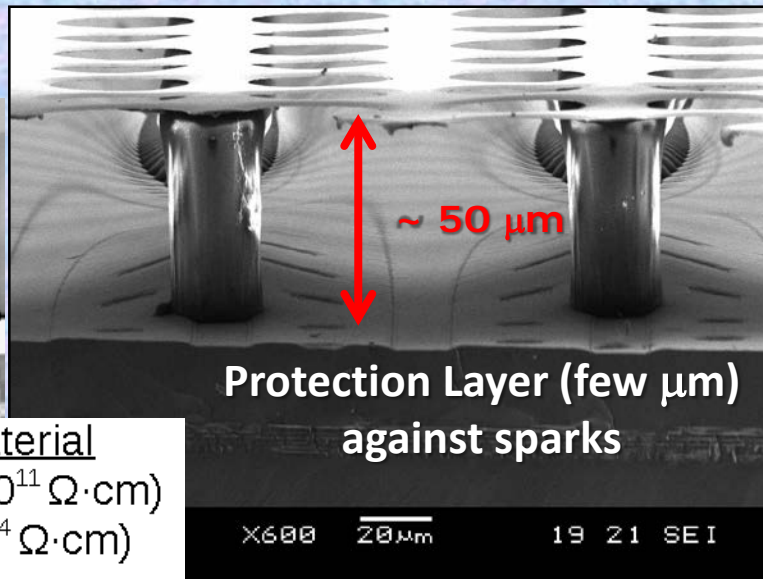
# Pixel Readout of MPGDs: "InGrid" Concept

"InGrid" Concept: By means of advanced wafer processing-technology **INTEGRATE** MICROMEGLAS amplification grid directly **on top of CMOS** ("Timepix") ASIC

3D Gaseous Pixel Detector  $\rightarrow$  2D (pixel dimensions)  $\times$  1D (drift time)

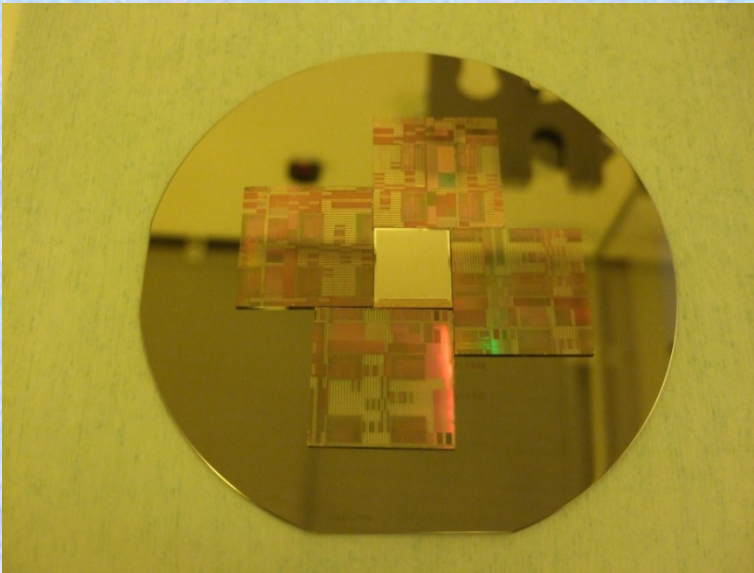


high resistive material  
15  $\mu\text{m}$  aSi:H ( $\sim 10^{11} \Omega \cdot \text{cm}$ )  
8  $\mu\text{m}$  Si<sub>3</sub>N<sub>4</sub> ( $\sim 10^{14} \Omega \cdot \text{cm}$ )



# “InGrid” Technology and “Driving” Developments

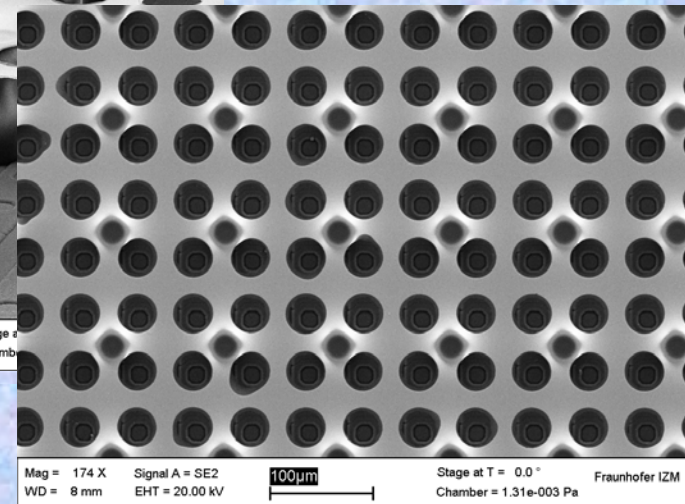
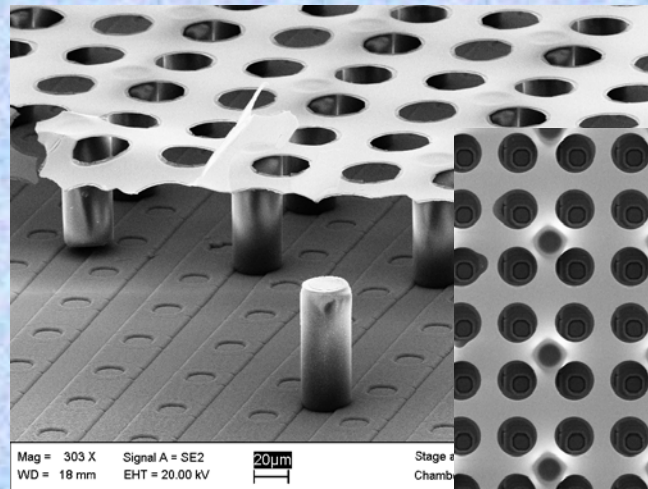
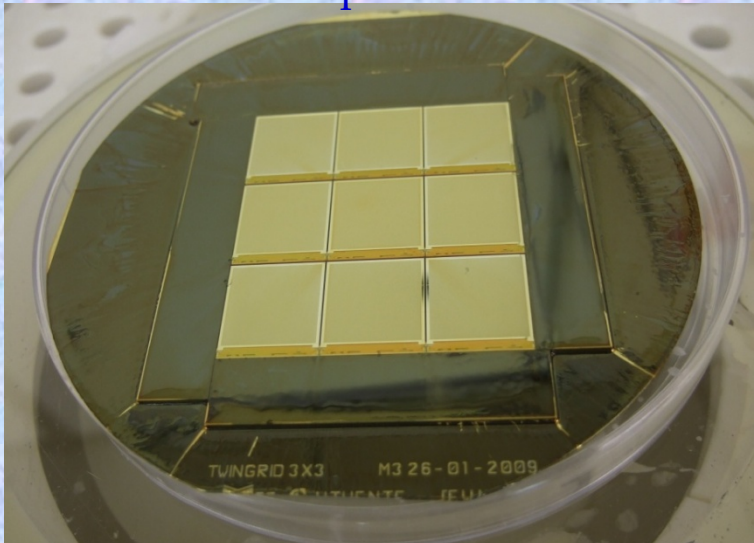
2005: Single “InGrid” Production



Since 2011: Major Step Forward →  
InGrid Production on a wafer level (107 chips)



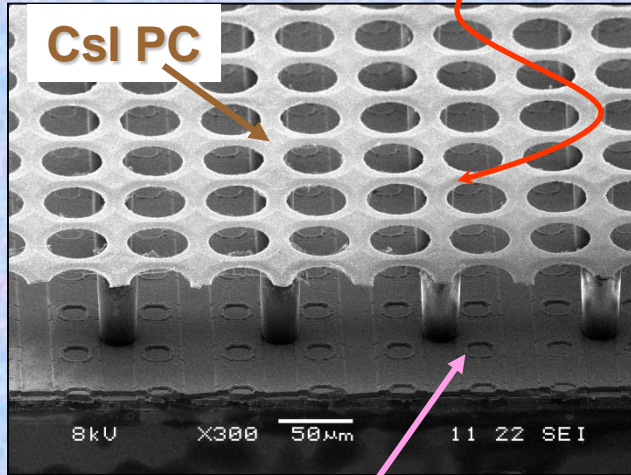
2009: “InGrid” Production on a  
3 x 3 Timepix Matrix





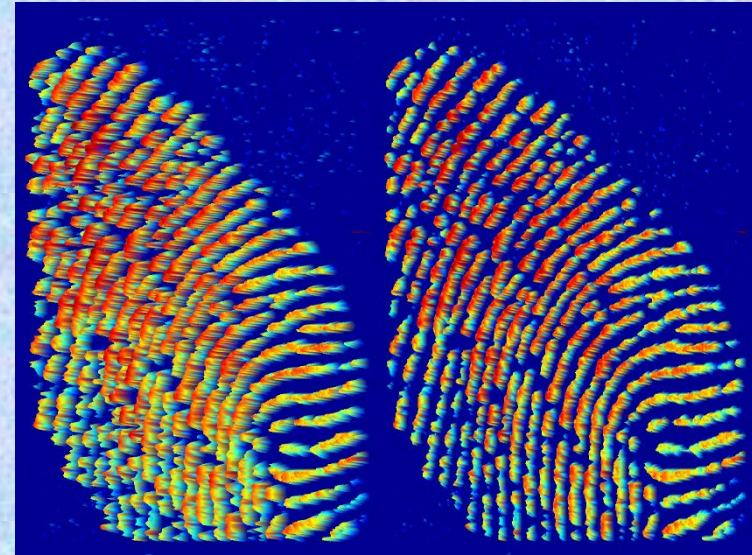
# Photosensitive Detector: Integrating Ingrid and CMOS readout

MICROME GAS (InGrid)  
covered with CsI

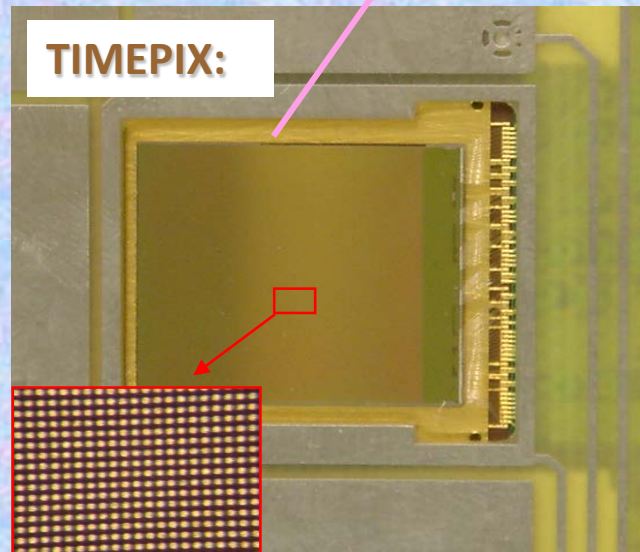


Ingrid without CsI

UV absorbed  
by the  
fingerprint  
on the window

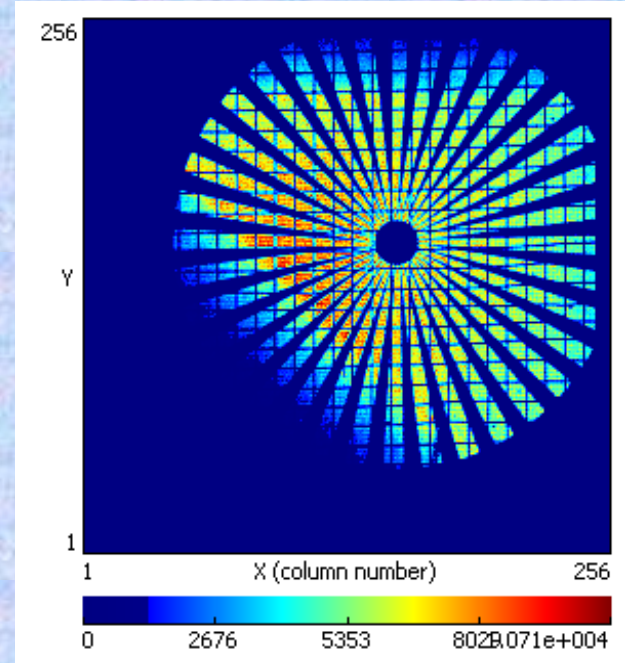


*M. Fransen, RD51 Mini-Week, Sep. 23-25, 2009, WG2 Meeting*



Ingrid with CsI PC:

2D UV Image  
of a 10mm  
diameter mask



Chip area: 14x14mm<sup>2</sup>.  
(256x256 pixels of 55x55 µm<sup>2</sup>)

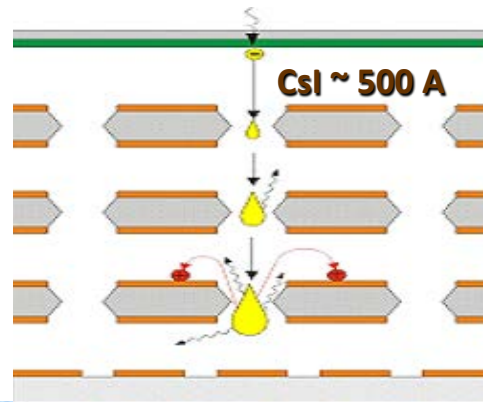
# MPGD-Based Gaseous Photomultipliers (GPM)

GEM Gaseous Photomultipliers (GEM+CsI photocathode) to detect single photoelectrons

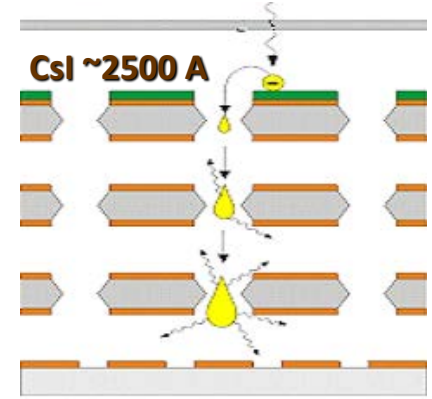
## Multi-GEM Gaseous Photomultipliers:

- ❖ Largely reduced photon feedback (can operate in pure noble gas &  $\text{CF}_4$ )
- ❖ Fast signals [ns]  $\rightarrow$  good timing
- ❖ Excellent localization response
- ❖ Able to operate at cryogenic T

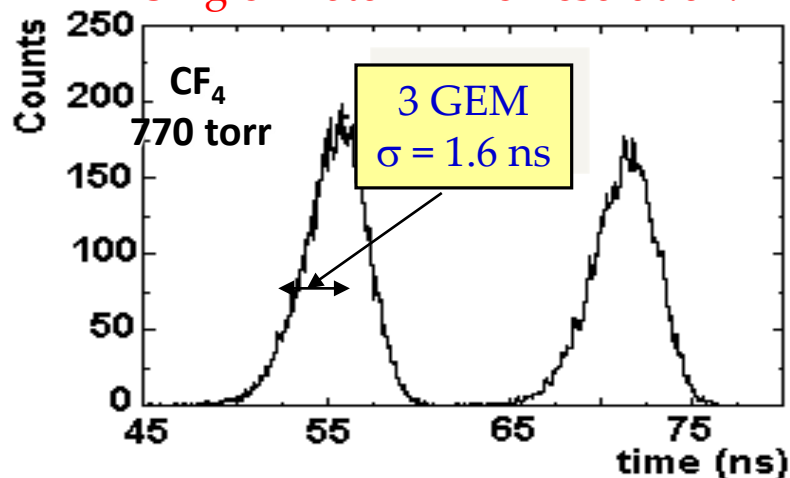
Semitransparent Photocathode (PC)



Reflective Photocathode (PC)

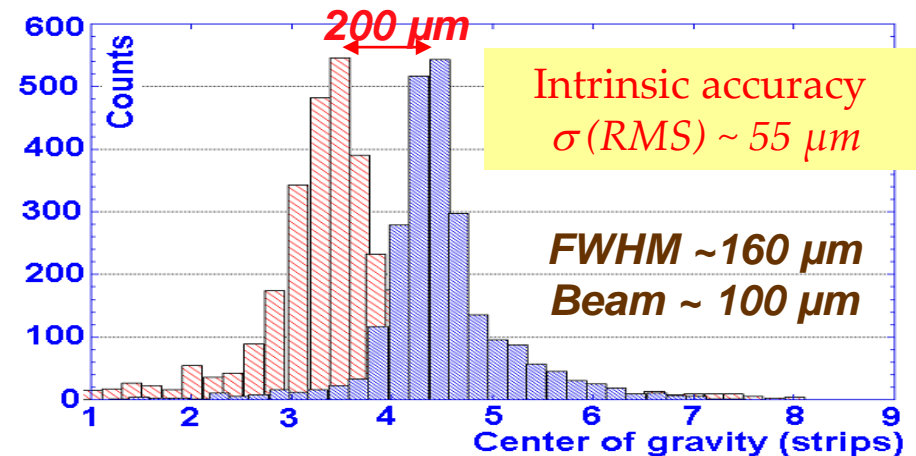


## Single Photon Time Resolution:



Micromegas:  $\sigma \sim 0.7$  ns with MIPs

## Single Photon Position Accuracy:



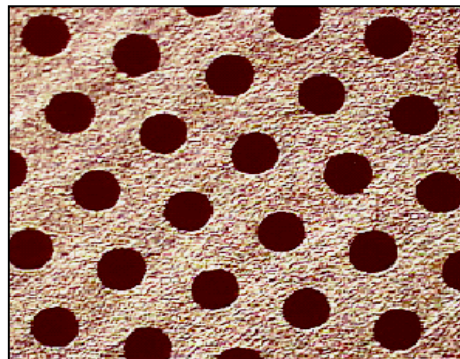


# Thick-GEM Multipliers (THGEM)

Simple & Robust → Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching

## STANDARD GEM

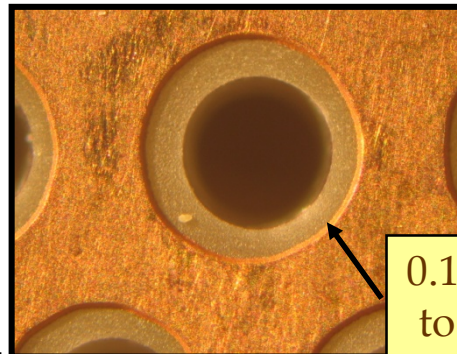
$10^3$  GAIN IN SINGLE GEM



1 mm

## THGEM

$10^5$  gain in single-THGEM



0.1 mm rim  
to prevent  
discharges

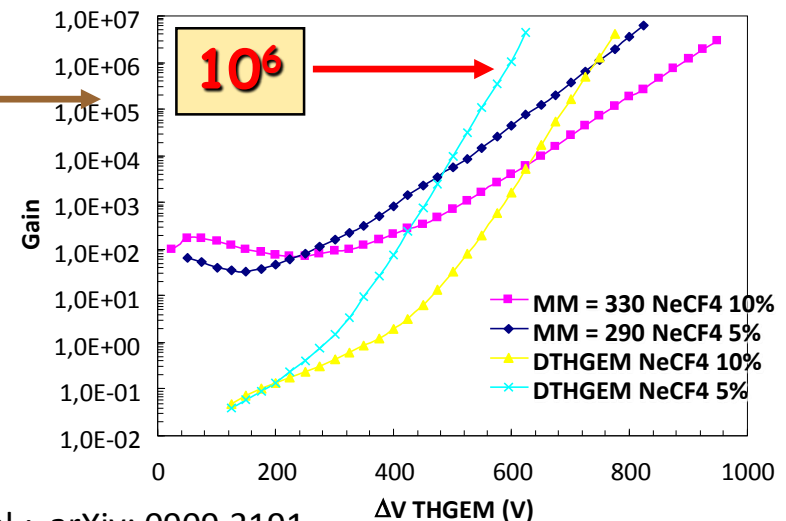
Other groups developed similar hole-multipliers:

- Optimized GEM:  
L. Periale et al.,  
NIM A478 (2002) 377.

- LEM: P. Jeanneret,  
- PhD thesis, 2001.

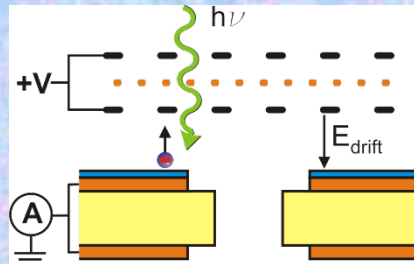
- Effective **single-electron** detection (high gas gain  $\sim 10^5$  ( $>10^6$ ) @ **single (double)** THGEM)
- **Few-ns** RMS time resolution
- **Sub-mm** position resolution
- **MHz/mm<sup>2</sup>** rate capability
- **Cryogenic operation: OK**
- Gas: **molecular and noble gases**
- Pressure: **1mbar - few bar**

Double THGEM or THGEM/Micromegas



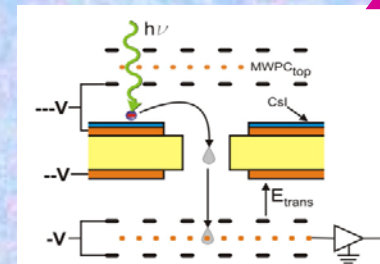
# THGEM Photon Detectors for RICH: Efficiency Evaluation

$$\text{Photon Detection Efficiency} = \text{QE (CsI)} * \text{Photo-current} \left( \frac{\text{Gas}}{\text{Vacuum}} \right) * \text{Electron Collection Efficiency}$$



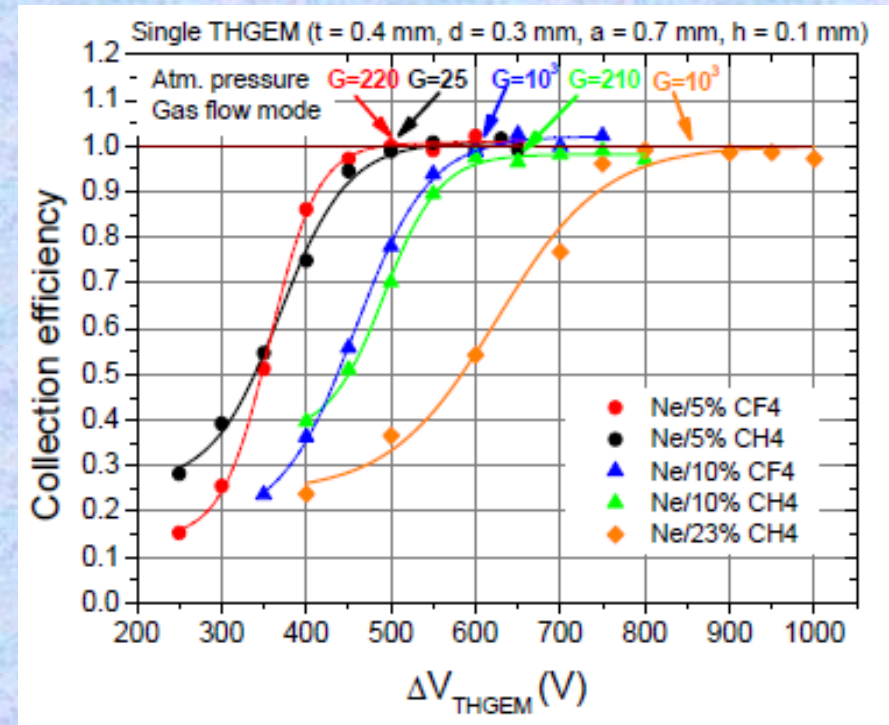
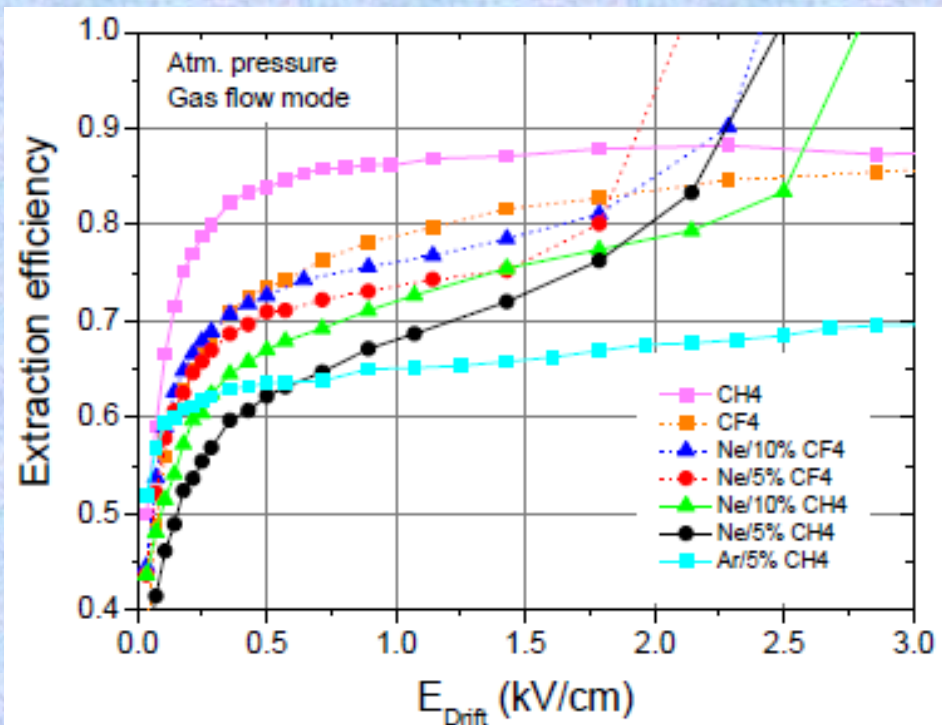
PE efficiency  
extraction  
into the gas  
vs vacuum:

$$\varepsilon_{extr} = \frac{I_{gas}}{I_{vac}}$$



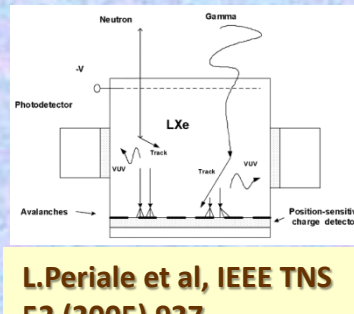
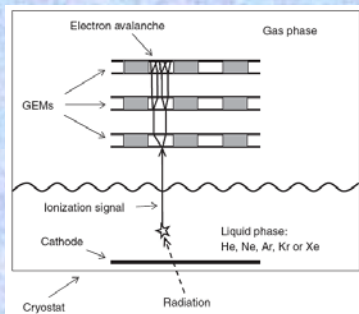
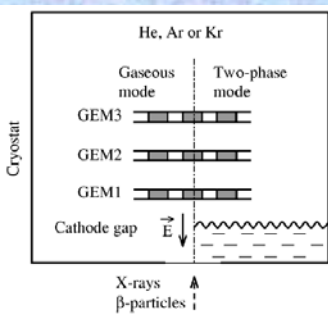
Single PE  
collection efficiency  
into THGEM holes:

$$\varepsilon_{coll} = \frac{N_{THGEM}}{N_{ref}}$$

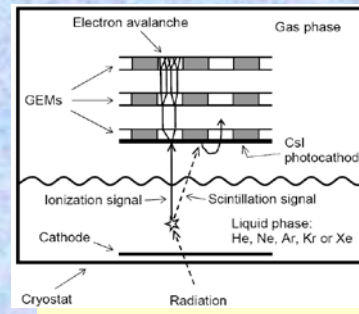




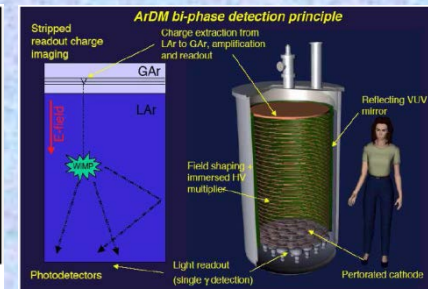
# MPGD-Based Cryogenic Avalanche Detectors: Concept Gallery



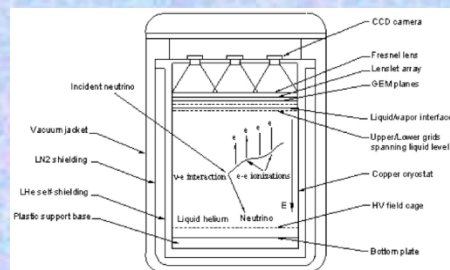
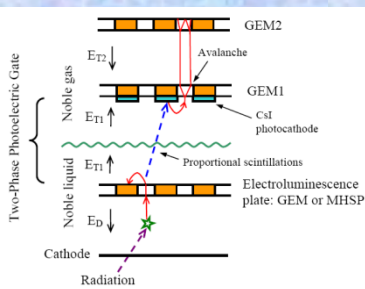
L.Periale et al, IEEE TNS 52 (2005) 927



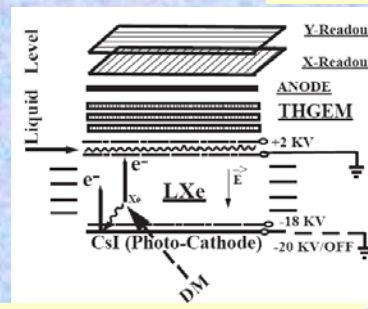
A.Bondar et al, NIMA 556 (2006) 273



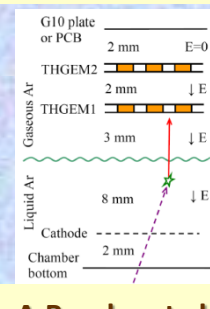
A.Rubbia, J. Phys. Conf. Ser. 39 (2006) 129



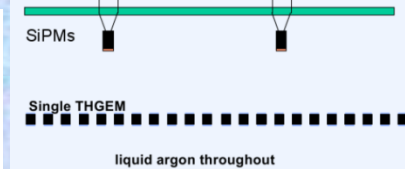
Y.L.Ju et al, Cryogenics 47 (2007) 81



M.Gai et al, Eprint arxiv:0706.1106 (2007)



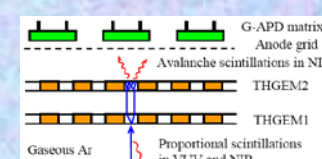
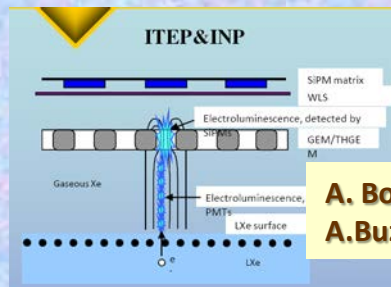
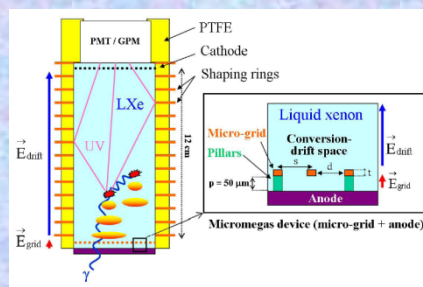
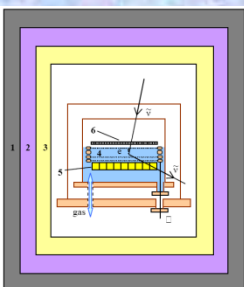
A.Bondar et al, JINST 3 (2008) P07001



P.K.Lightfoot et al, JINST 4 (2009) P04002

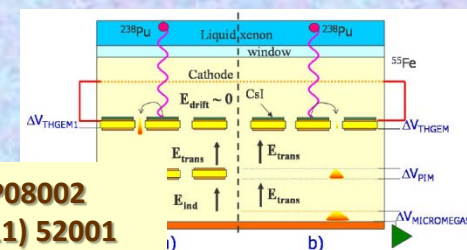
N.McConkey et al, IPRD 2010, Siena, Italy; Nucl. Phys. B Proc. Suppl. 215 (2011) 255

A.Buzulutskov, A.Bondar, JINST 1 (2006) P08006



A. Bondar et al, JINST 5 (2010) P08002

A.Buzulutskov et al, EPL 94 (2011) 52001

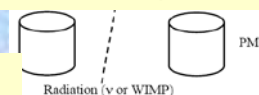


S. Duval et al, JINST 6 (2011) P04007

D.Akimov et al, JINST 4 (2009) P06010

S. Duval et al, JINST 4 (2009) P12008

D.Akimov, NIMA 628 (2011) 50

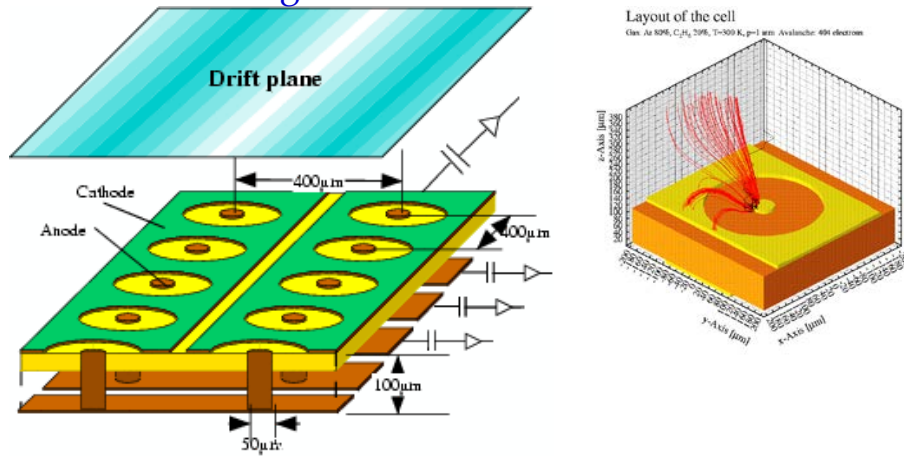


# Micro-Pixel Chamber ( $\mu$ PIC) at Kobe University

$\mu$ -PIC: micro pixel gas chamber

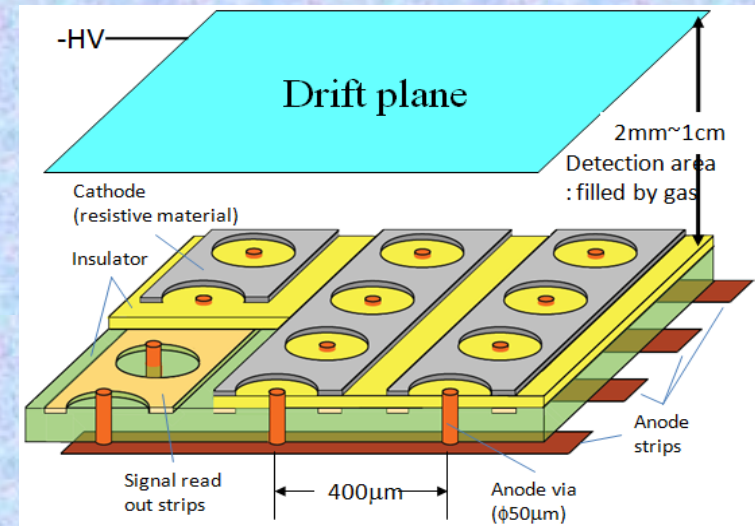
- ❖ Area: 10x10cm – 30x30cm
- ❖ Readout pitch :400 $\mu$ m
- ❖ Production using PCB technology

Invented by A.Ochi, T.Tanimori (NIMA471 (2001) 264)  
Application: X-ray imaging, Gamma camera,  
Medical RI tracing

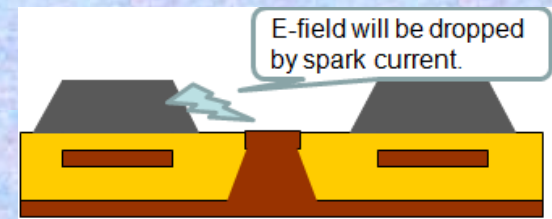
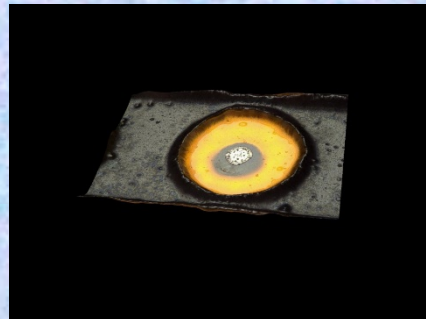
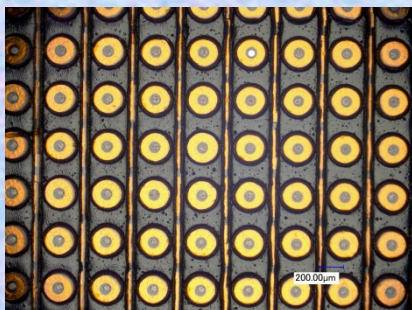


**NEW:  $\mu$ -PIC design with resistive cathode:**

- Cathode patterns are formed by resistive material.
- Large current from spark reduce the e-field, and spark will be quenched.
- This design provide one promising possibility of **MIP detector under hadronic background**



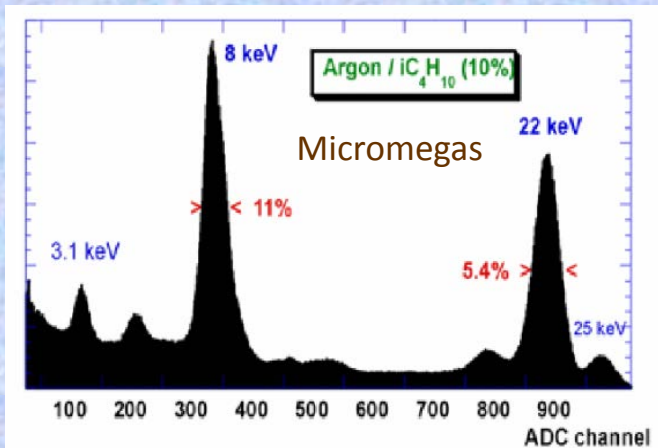
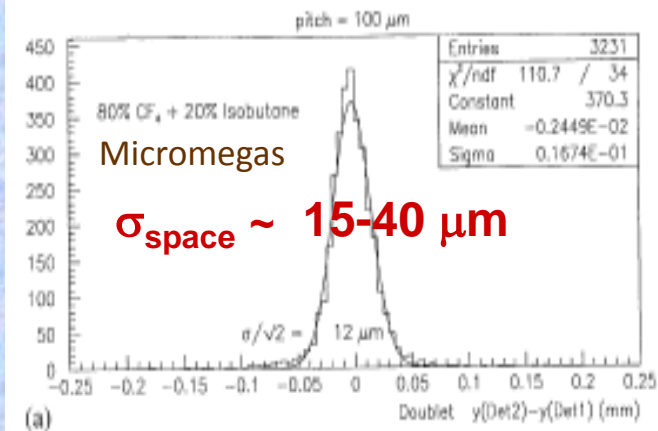
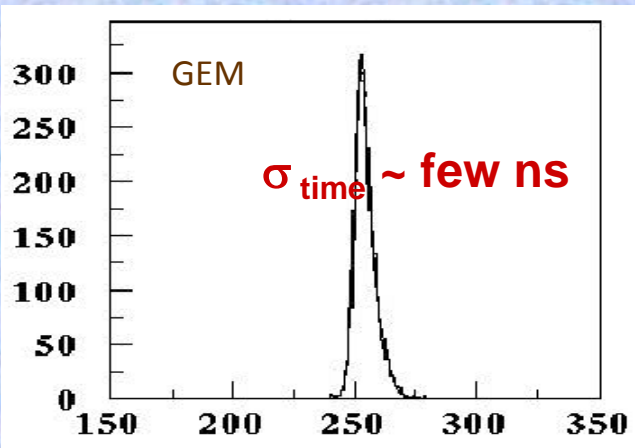
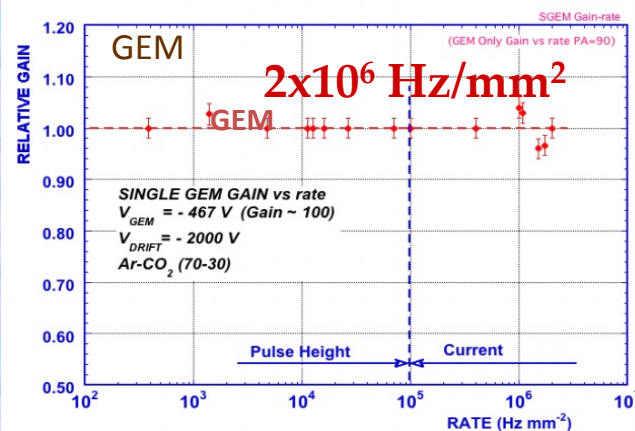
**Surface pictures of resistive  $\mu$ PIC:**





# Why Micro-Pattern Gaseous Detectors are so attractive ...

- High Rate Capability
- High Gain
- High Space Resolution
- Good Time Resolution
- Good Energy Resolution
- Excellent Radiation Hardness
- Ion Backflow Reduction
- Photon Feedback Reduction



One of the recent reviews describing the progress of the RD51 collaboration:

## MICRO-PATTERN GASEOUS DETECTOR TECHNOLOGIES AND RD51 COLLABORATION

MAXIM TITOV

CEA Saclay, DSM/IRFU/SPP, 91191 Gif sur Yvette, France  
maxim.titov@cea.fr

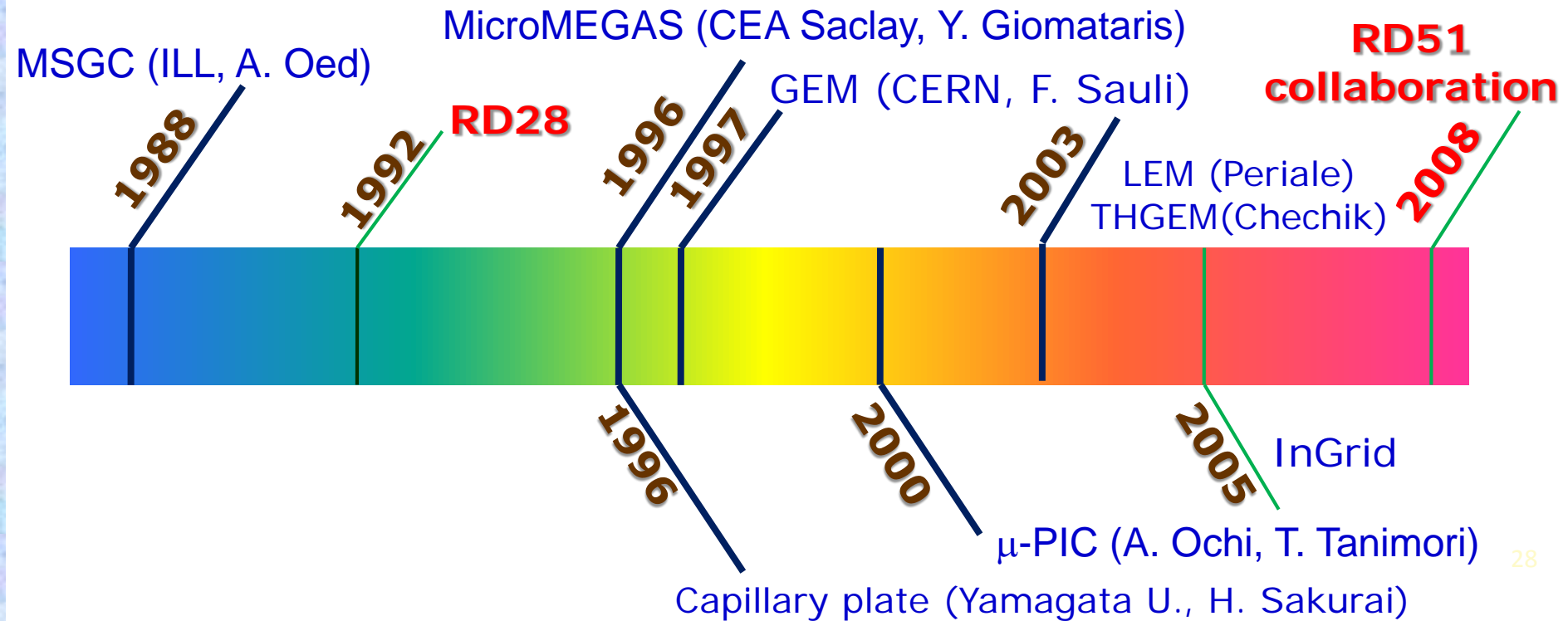
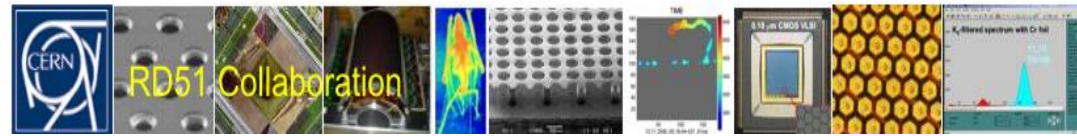
LESZEK ROPELEWSKI

CERN PH, CH-1211, Geneva 23, Switzerland  
leszek.ropelewski@cern.ch

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Vol. 28, No. 13 (2013) 1340022 (25 pages)  
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DOI: 10.1142/S021773231340022

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# Historical Roadmap of the MPGD Technologies and RD51 Collaboration



28

- Many of the Micro-Pattern Gaseous Detector Technologies were introduced before the RD51 Collaboration was founded
- With more techniques becoming available (or affordable), new detection concepts are being introduced and the existing ones are substantially improved



The **main objective** is to advance **MPGD technological development** and associated electronic-readout systems, for applications in basic and applied research": <http://rd51-public.web.cern.ch/rd51-public>



❖ Large Scale R&D program to advance MPGD Technologies

❖ Access to the MPPGD "know-how"

❖ Foster Industrial Production

- More than **80 groups**
- More than **400 people**
- National and International **Laboratories**
- National **Institutes and Universities**

# Summary of the RD51 Achievements (2008 – 2013)



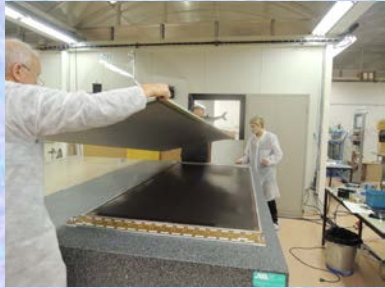
- Consolidation of the Collaboration and **MPGD Community Integration** (> 80 institutes, 450 members);
- Major progress in MPPGD Technologies: Large area GEM (single mask), Micromegas (resistive) and THGEM; picked up by experiments, including LHC upgrades;
- **Secured future** of the MPPGD Technologies development through the TE MPE **workshop upgrade** and FP7 AIDA contribution
- Contacts with industry for large volume production; MPGD industrialization and first industrial runs
- Major improvement to the MPPGD **simulation** software framework **for small-scale structures** for applications;
- Development of common, scalable readout electronics (SRS); many developers and > 50 user groups; **Production** (PRISMA company and availability through CERN store); **Industrialization** (re-design of SRS in ATCA in EISYS)
- Infrastructure for common RD51 test beam and facilities (> 20 user groups);



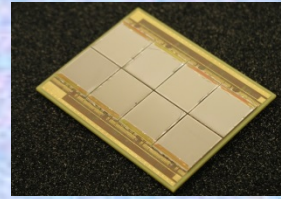
# Future RD51 Collaboration Activities (beyond 2013)



Large Area Detectors  
Assembly Optimization

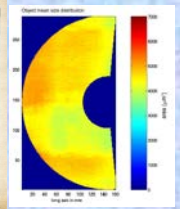


**WG1:**



**WG2:**

RD51 Common Projects  
Generic R&D, QA  
Long Term Stability



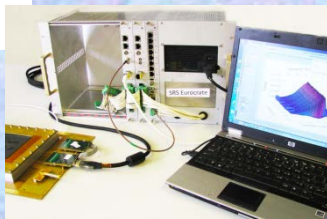
**WG4:**

Software Tools  
and  
Simulations

**RD51**

**WG5:**

MPGD  
Electronics



**WG3/NEW WG:**

**WG7:**

- Conferences / Schools
- Academia-Industry Matching Events

**WG6:**



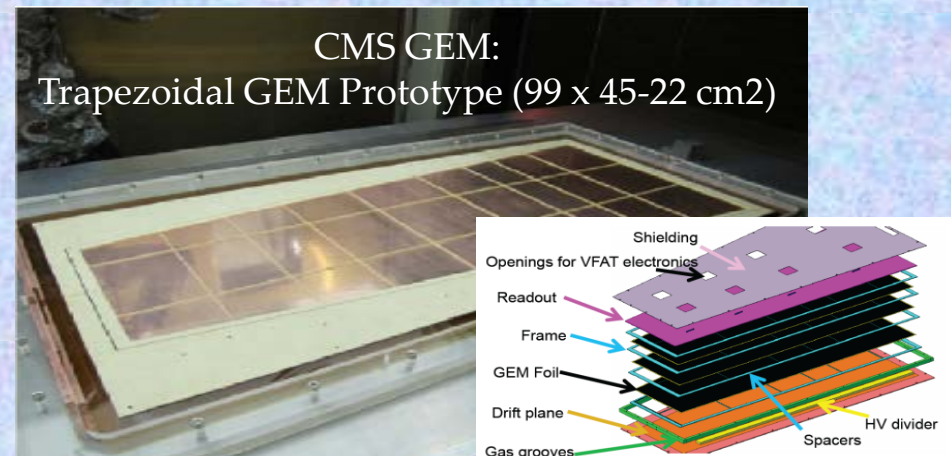
CERN MPPD  
Workshop,  
Quality Control  
and  
Industrialization

RD51 Common  
Test Beam and Lab  
Facilities



# MPGD Technologies for Energy Frontier (HL-LHC, LC)

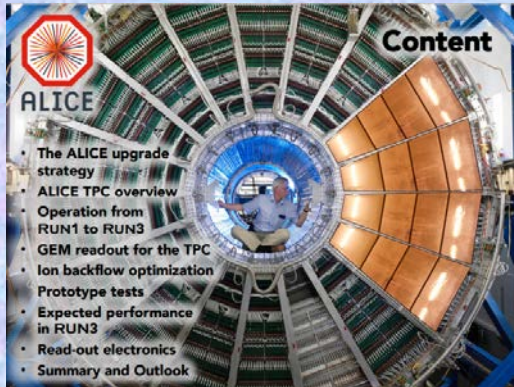
	Vertex	Inner Tracker	PID/ photo- det.	EM CALO	HAD CALO	MUON Tracking	MUON Trigger
ATLAS						Micromegas	Micromegas
CMS					Backing-HE (GEM, MM)	GEM	GEM
TOTEM						GEM	GEM
LHCb							GEM
ALICE		TPC (GEM)					
Linear Collider		TPC(MM,GEM, InGrid)			DHCAL(MM, GEM,THGEM)		





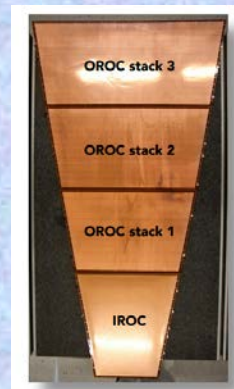
# WG1: Examples of CERN/LHC Upgrades ("large achievement for MPGD community")

## ALICE (GEM)



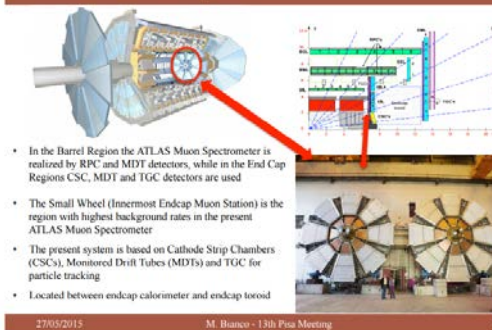
**Content**

- The ALICE upgrade strategy
- ALICE TPC overview
- Operation from RUN1 to RUN3
- GEM readout for the TPC
- Ion backflow optimization
- Prototype tests
- Expected performance in RUN3
- Read-out electronics
- Summary and Outlook



## ATLAS NSW (Micromegas)

### The ATLAS Muon Spectrometer and the Small Wheel



- In the Barrel Region the ATLAS Muon Spectrometer is realized by RPC and MDT detectors, while in the End Cap Regions CSC, MDT and TGC detectors are used
- The Small Wheel (Innermost Endcap Muon Station) is the region with highest background rates in the present ATLAS Muon Spectrometer
- The present system is based on Cathode Strip Chambers (CSCs), Monitored Drift Tubes (MDTs) and TGC for particle tracking
- Located between endcap calorimeter and endcap toroid

27/03/2015 M. Bianco - 13th Pisa Meeting



### IBF optimized configuration (2)

- Satisfactory performance could not be achieved with 3 GEM stack
- Best results in terms of **IBF and energy resolution**

Cover electrode			
QEM 1 (20)		$E_{10}$	
QEM 20 (7)		$E_{11}$	
QEM 5 (7)		$E_{12}$	
QEM 4 (7)		$E_{13}$	
Post place		$E_{14}$	
Strong beam			

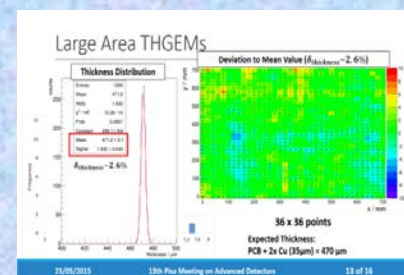
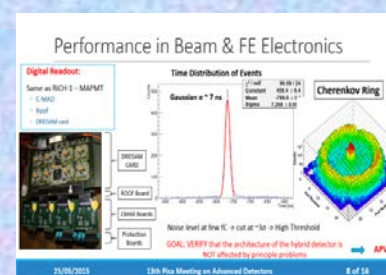
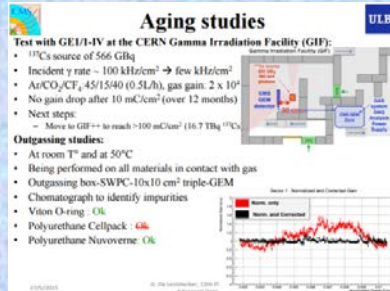
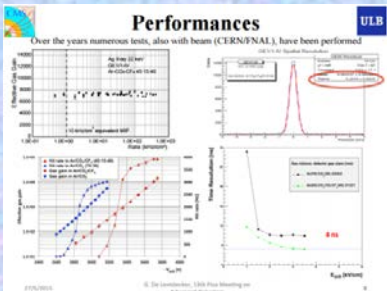
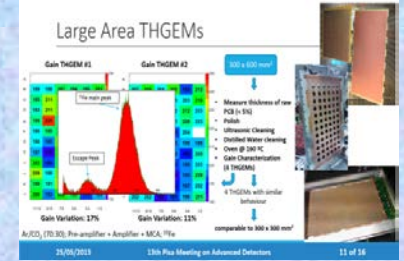
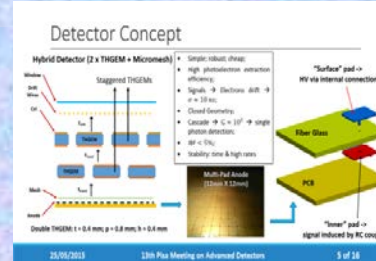
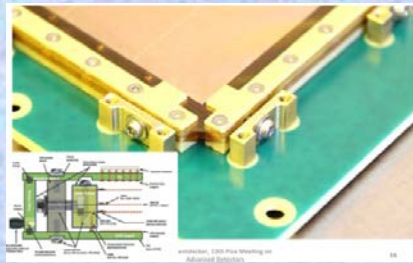
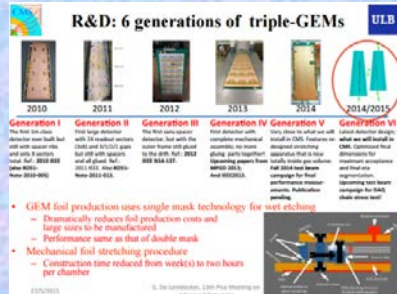
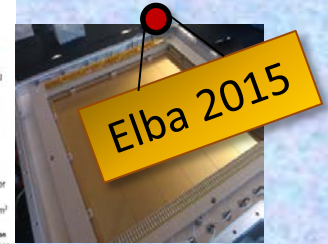
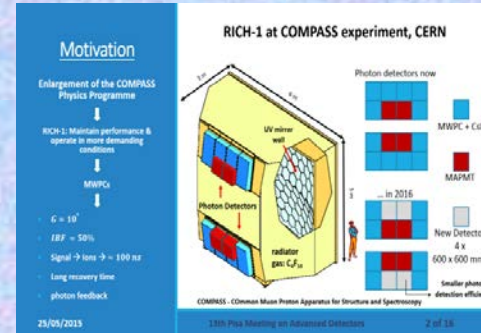
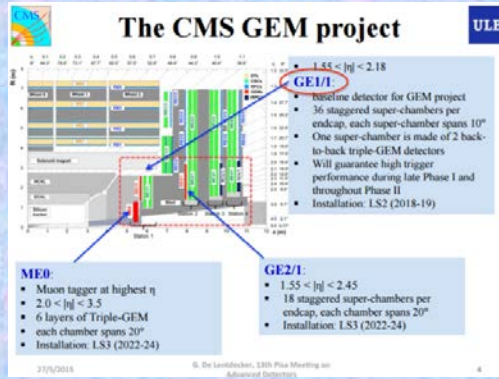
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## WG1: Examples of CERN/LHC Upgrades (“large achievement for MPGD community”)

# CMS (GEM)

# COMPASS RICH-1 (THGEM+MM)



LHC Upgrades: Original R&D efforts emerged from RD51 activities.

Today: production phase under the project effort , access to RD51 facilities (laboratory, test beam, workshops) and tools (simulation, electronics,...) to facilitate this particular phase

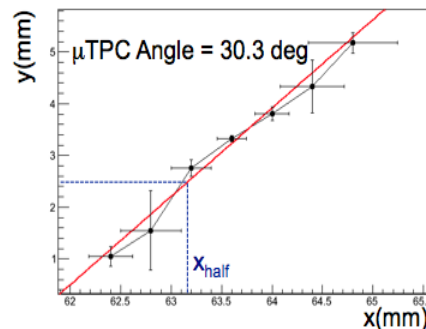
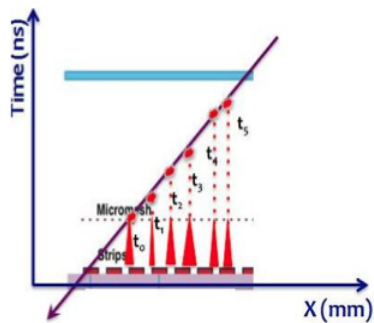


# Resistive Micromegas Performace: Resolution vs Track Angle

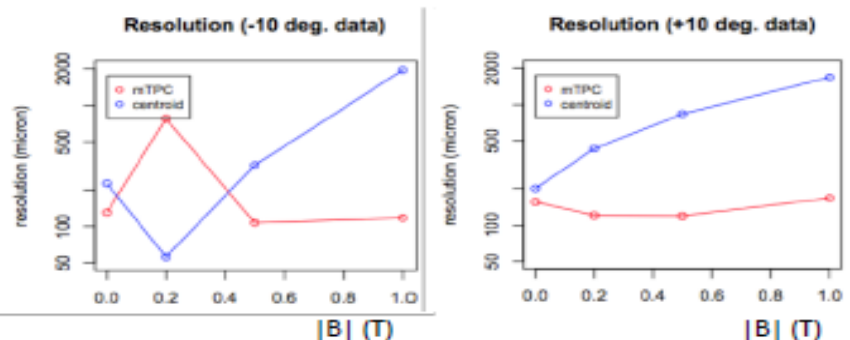
- Using charge amplitude (Centroid hit)
- Spatial resolution rapidly decreases for inclined tracks if the cluster centroid (e.g., charge weighting) is used; small strip pitch does not help

- Using time information (TPC segment)

Measuring the arrival time of the signals opens a new dimension; in this case the MM functions like a TPC  
 => Track vectors/plane for inclined tracks



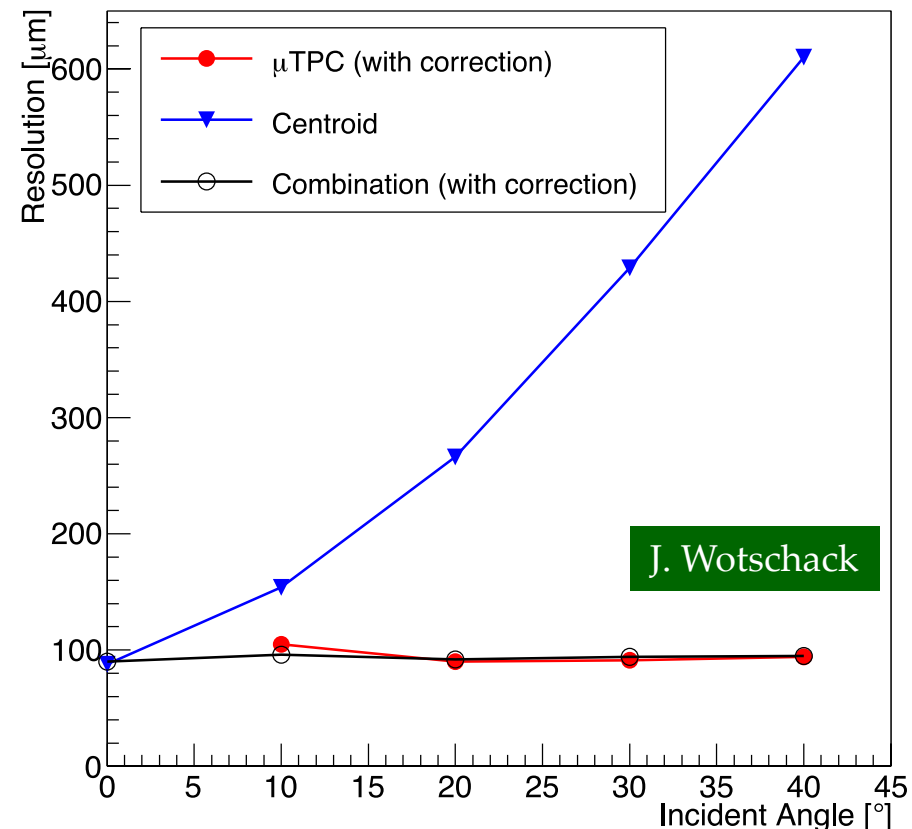
Spatial resolution vs magnetic field:



Combination of centroid & TPC →

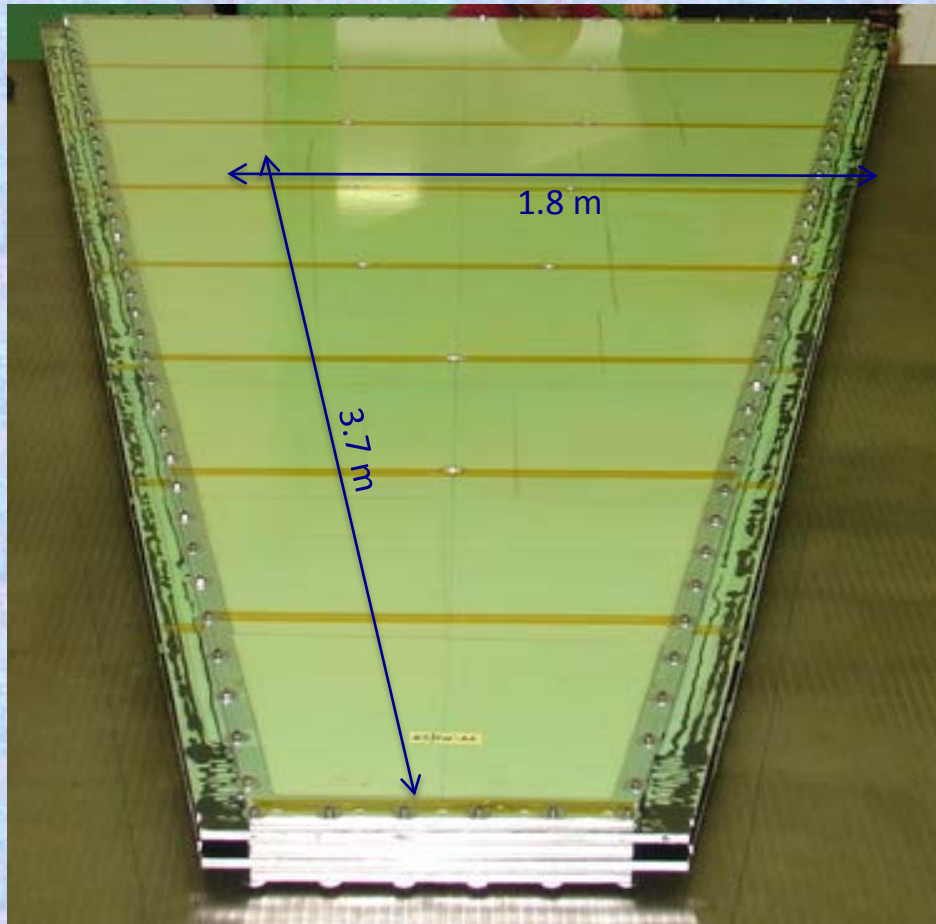
spatial resolution < 100  $\mu\text{m}$  independently of track incident angle !

## Single Plane Spatial Resolution



Range of track angles in NSW

# Micromegas for ATLAS NSW: Full Sector Mechanical Prototype (CERN)



Test of segmented FR4 skin glueing with different stiffeners

Will serve for deformation studies



Stress and deflection test



# GEM Technology: From GE 1/1 to GE1/1-v6 Prototypes

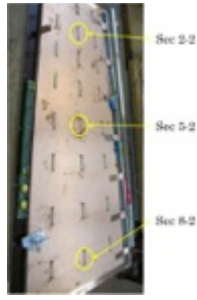


2010

**Generation I**

The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total.

Ref.: 2010 IEEE (also RD51-Note-2010-005)

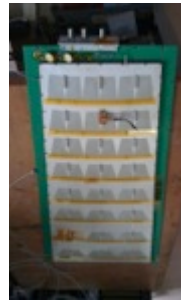


2011

**Generation II**

First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued.

Ref.: 2011 IEEE. Also RD51-Note-2011-013.

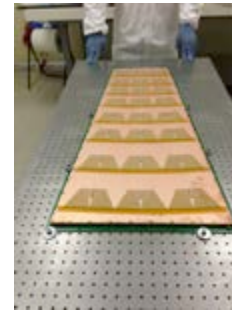


2012

**Generation III**

The first sans-spacer detector, but with the outer frame still glued to the drift.

Ref.: 2012 IEEE N14-137.



2013

**Generation IV**

First detector with complete mechanical assembly; no more gluing parts together!

MPGD 2013; and IEEE2013.



2014

**Generation V**

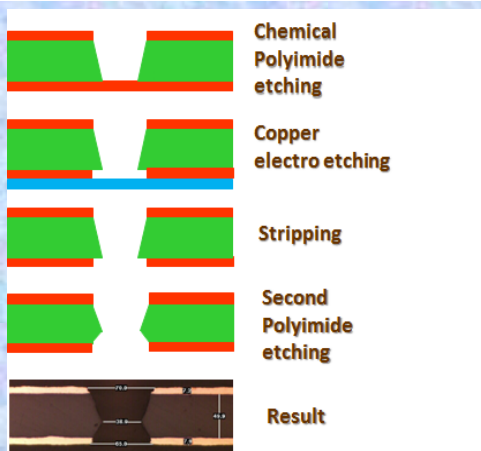
Nearly final CMS design: stretching apparatus that is now totally inside gas volume. **Ongoing test beam campaign for final performance measurements.**



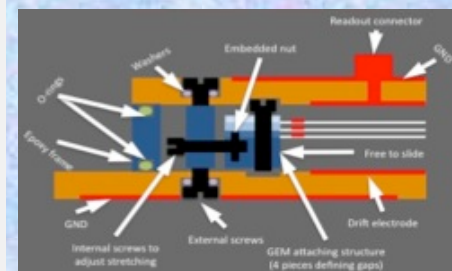
2014/2015

**Generation VI**

Latest detector design; **to be installed in CMS.** Optimized final dimensions for max. acceptance and final eta segmentation. **Ongoing test beam campaign for DAQ**



- GEM foil production uses single mask technology for wet etching
  - Dramatically reduces foil production costs and allows large sizes to be manufactured
- NS2 assembly technique developed
  - Construction time reduced from week(s) to two hours per chamber



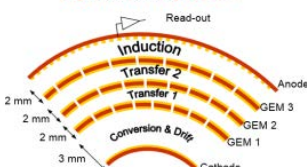
A. Sharma

# Consolidation of existing structures: Cylindrical MPGDs as an example

## KLOE2 Inner Tracker

- 5 independent tracking layers 15 to 25 cm from IP to improve vertex reconstruction
- $\sigma_{\phi} = 200 \mu\text{m}$  and  $\sigma_z = 500 \mu\text{m}$  spatial resolutions with XV strips-pads readout
- 700 mm active length
- 1.5%  $X_0$  total radiation length in the active region with Carbon Fiber supports
- $\varnothing 300 \times 352\text{mm}$  prototype with Std GEM has been assembled and tested

### Cylindrical Triple GEM



Realized as an



## CLAS12 TEAM AT SACLAY

- D. Attie, S. Aune, J. Giraud, R. Graneli, C. Lahonde-Hamdoun, I. Mandjavidze, O. Meunier, S. Procureur, M. Riallot, J-Y Rousse, F. Sbatle, M. Vandenbroucke

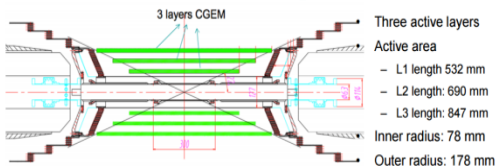


## omegas

5

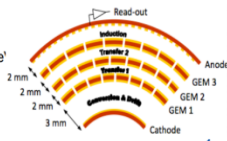


## CGEM detector for BESIII

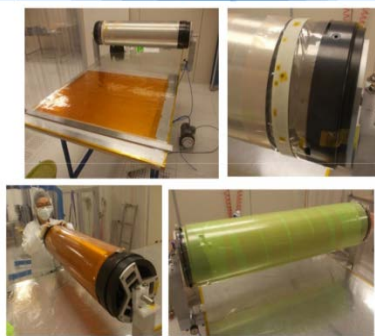


### Requirements

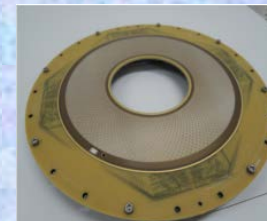
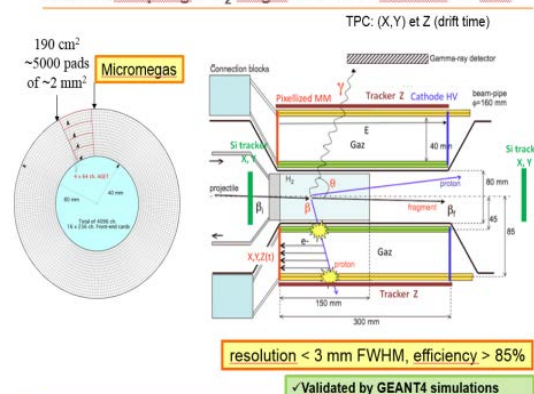
- Rate capability:  $\sim 10^4 \text{ Hz/cm}^2$
- Spatial resolution:  $s_{xy} \sim 100 \mu\text{m}$ ;  $s_z \sim 1\text{mm}$
- Momentum resolution:  $s_p/P_1 \sim 0.5\%$  @  $1\text{GeV}$
- Efficiency  $\sim 98\%$
- Material budget  $\leq 1.5\%$  all layers
- Coverage:  $93\%$   $4\pi$
- Operation duration  $\sim 5$  years



## GEM foil assembly test



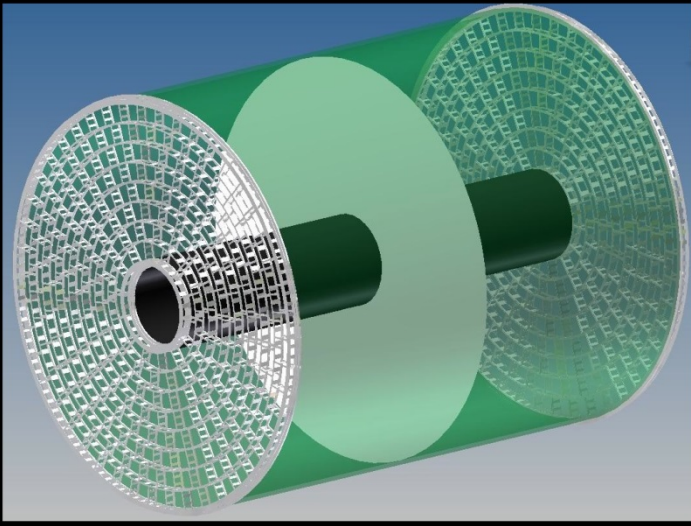
## MINOS: coupling a $\text{H}_2$ target to a TPC+Tracker+Si Det.



E. Oliveri



# MPGD Readout for the Time Projection Chamber at the ILC/CLIC



MPGDs are foreseen as TPC readout for ILC or CLIC (size of endcaps of  $\sim 10 \text{ m}^2$ ):

- **Standard “pad readout” ( $1 \times 6 \text{ mm}^2$ ):** 8 rows of det. modules ( $17 \times 23 \text{ cm}^2$ ); 240 modules per endcap
- **“Pixel readout” ( $55 \times 55 \mu\text{m}^2$ ):**  $\sim 100$ - $120$  chips per module  $\rightarrow$  25000-30000 per endcap

$1 \times 6 \text{ mm}^2$  pads

Backgrounds in CLIC TPC requires very small pixels ( $< 1 \times 1 \text{ mm}^2$ )

$100 \times 100 \mu\text{m}^2$  pixels

CLIC TPC  
Simulation  
(M. Killenberg)

**ILCTPC with MPGD-Readout:**  
(spatial resolution  $< 100 \mu\text{m}$  @ 5T)

- Laser-etched GEMs  $100 \mu\text{m}$  thick (‘Asian GEMs’)
- Wet-etched triple GEMs
- Resistive MM with dispersive anode
- GEM + pixel readout
- InGrid (integrated Micromegas grid with pixel readout)

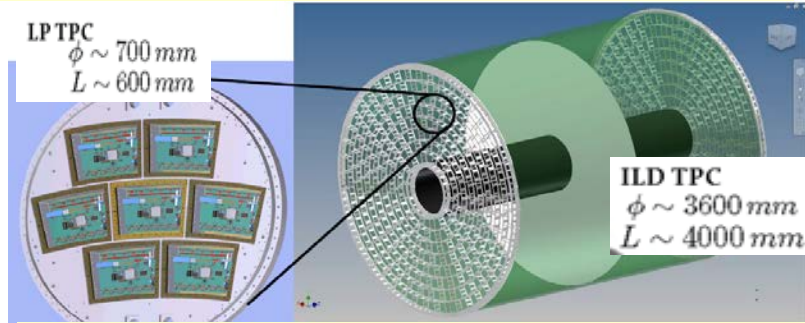
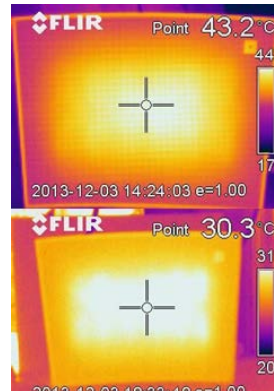
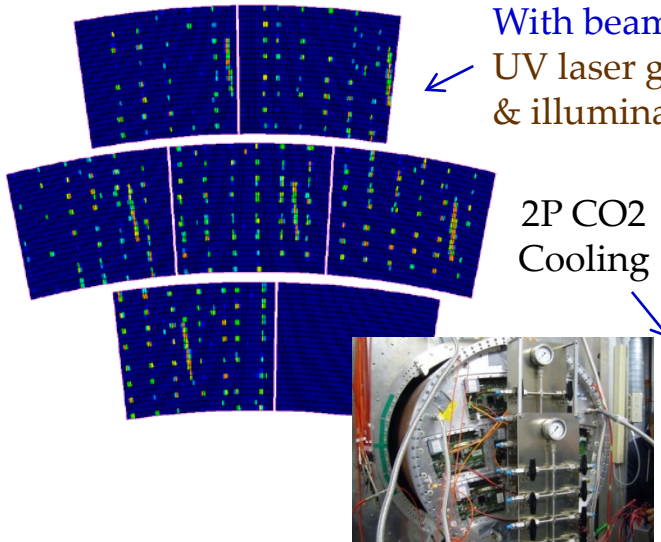
# MPGD-based “Pad Readout” for ILC TPC

Efforts to improve the modules design for all technologies. Several test beams campaigns:

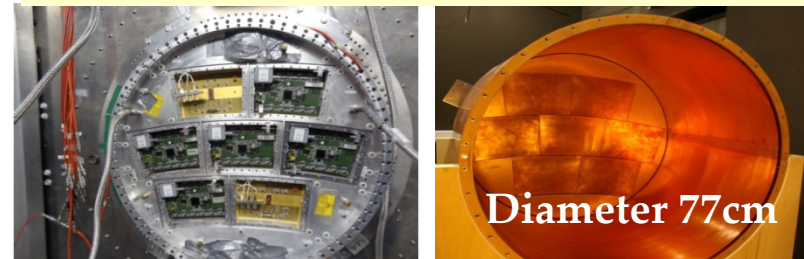
## ➤ 7 Micromegas modules with 2-phase CO<sub>2</sub> cooling

With beam and laser dots:  
UV laser generates MIP tracks  
& illuminate calibration spots

2P CO<sub>2</sub>  
Cooling

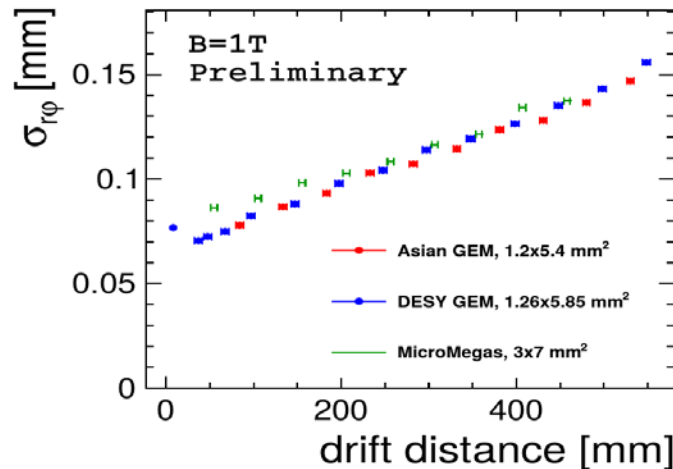


Large TPC Prototype with versatile endplate @ DESY

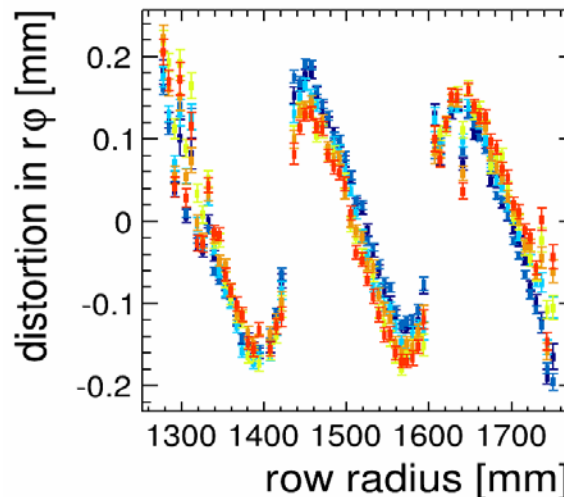


Diameter 77cm

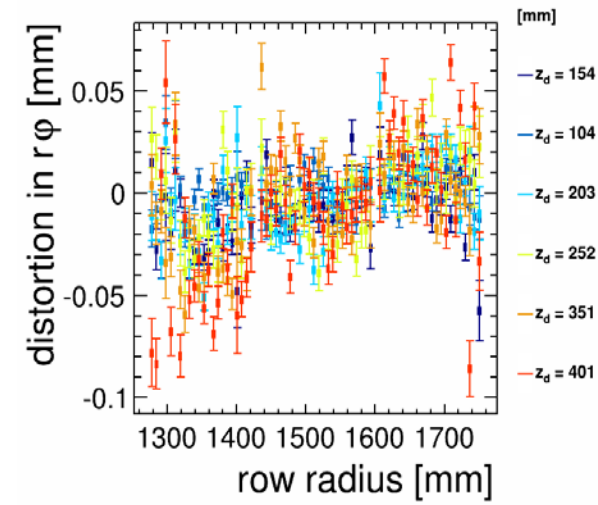
Goal for final TPC can be reached:  
GEM / MM performance similar



MM (B=0): Before correction



MM (B=0): After correction  
(note – different scale)





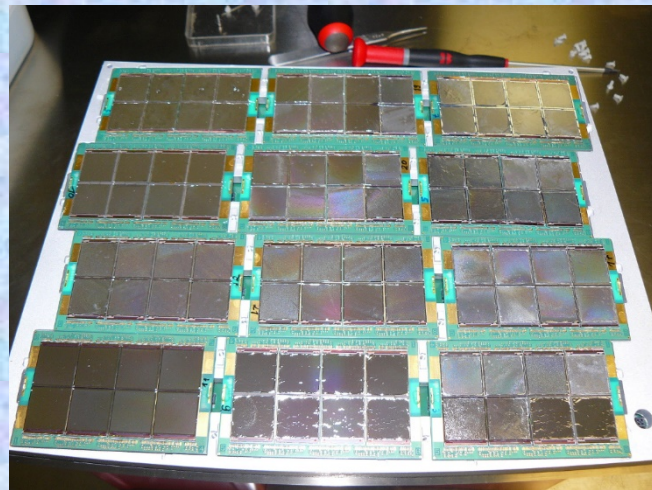
# MPGD-based “Pixel Readout” for ILC TPC

## LARGE AREA: 160 InGrid detector setup

- 3 modules: 1 x 96 InGrid, 2 x 24 InGrids
- Readout 5 SRS FECs

By design:

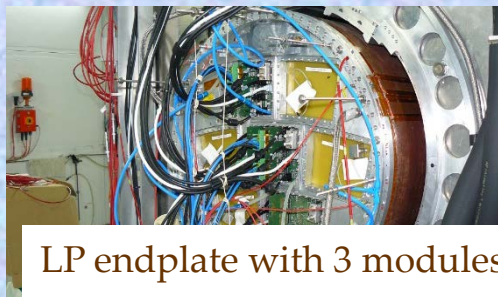
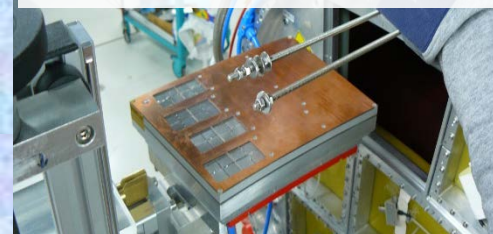
- Single electron detection
- Time-of-arrival measurement
- High granularity; Uniform gas gain



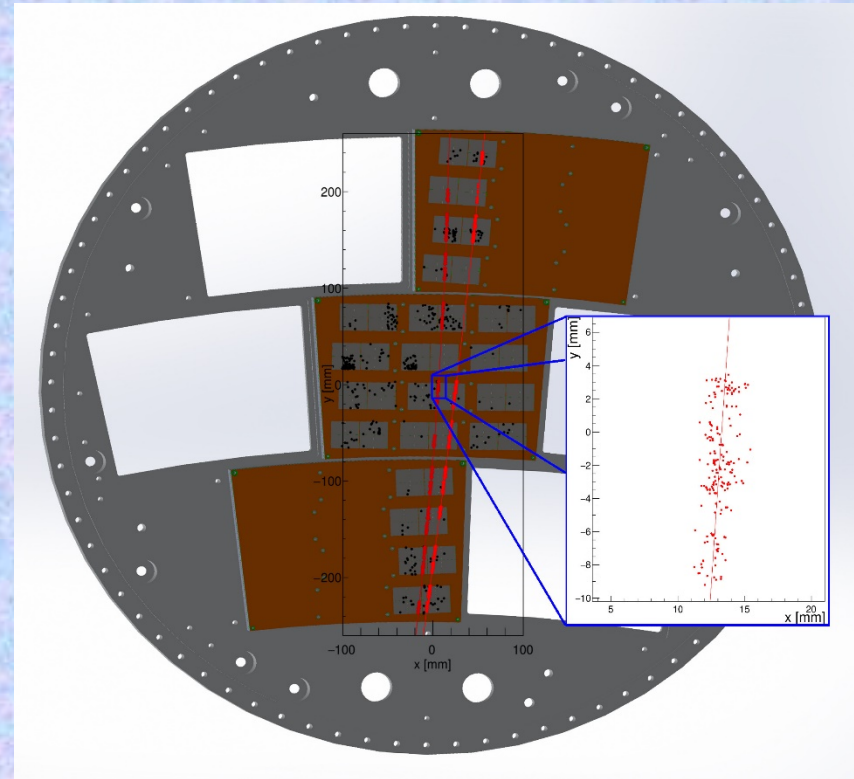
Module with  
96 InGrids  
on 12 „octobboards“

M. Lupberger

24 InGrid installation in LP



LP endplate with 3 modules



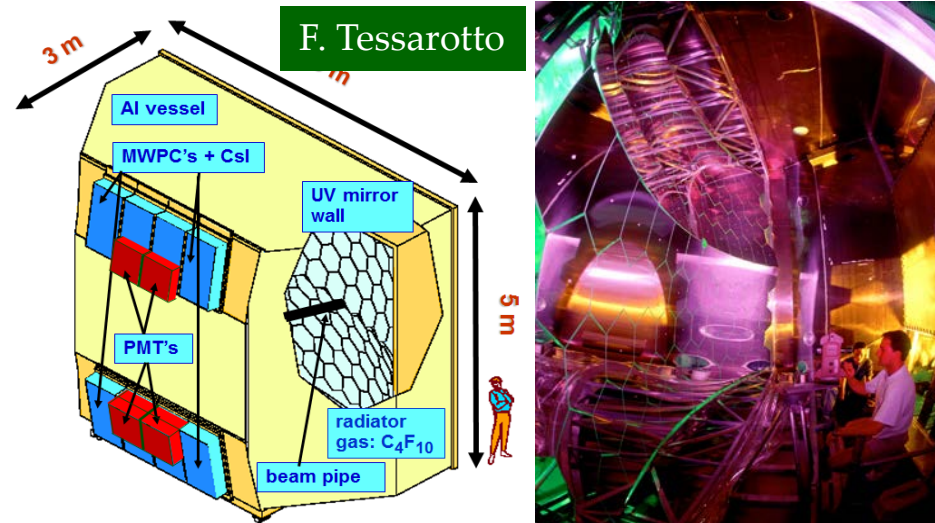
## Preliminary data analysis:

- Track reconstruction
  - straight and curved tracks
  - $\approx 3000$  hits per 50 cm track
- Physics properties of the TPC
  - field distortions; reliability
  - $dE/dx$  resolution; delta identification
  - single point resolution
  - momentum measurement

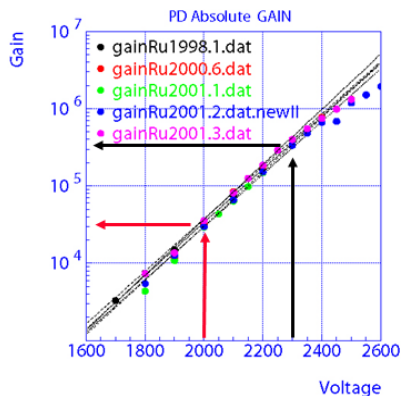
# COMPASS RICH I Upgrade: Long-Term Experience, Performance

## ❖ COMPASS RICH I:

- 1999-2000: 8 MWPC with CsI (RD26 @ CERN)



After a long-term fight for increasing electrical stability at high rates: **robust operation is not possible at gain  $\sim 10^5$**  because of photon feedback, space charge & sparks



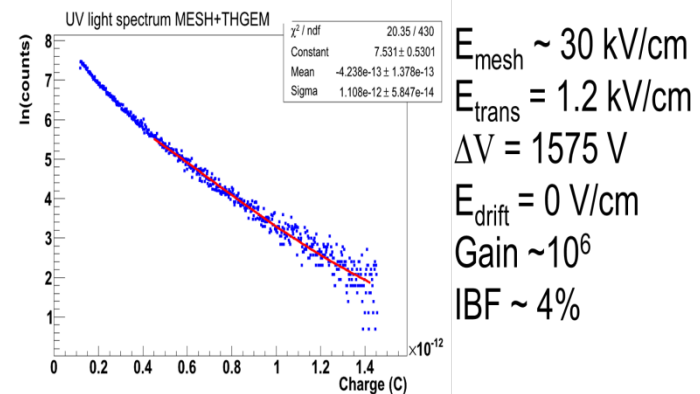
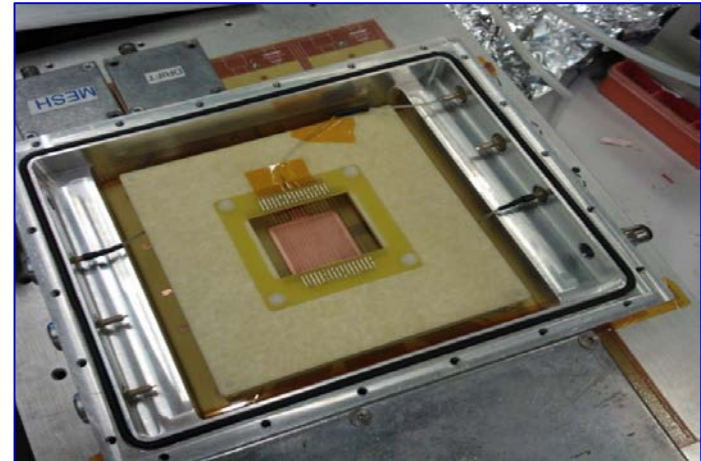
- ❖ beam off: stable operation up to  $> 2300$  V
- ❖ beam on: stable operation possible only up to  $\sim 2000$  V
- ❖ 2006: 4 central CsI+cathodes: remove and insert frames with MAPMTs and lense telescopes

PMTs not adequate  $\rightarrow$  only small demagnification factor allowed;  $5 \text{ m}^2$  of PMTs not affordable.

## ❖ UPGRADE OF COMPASS RICH I:

- MPGD-Photon Detectors are the best option

$\rightarrow$  **Micromegas + THGEM**, the hybrid architecture structure, is one of the most advanced scheme:



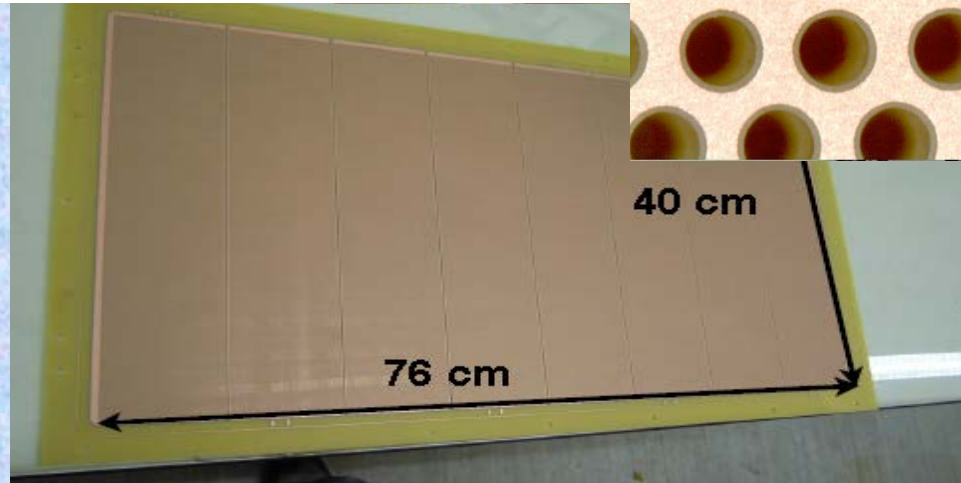
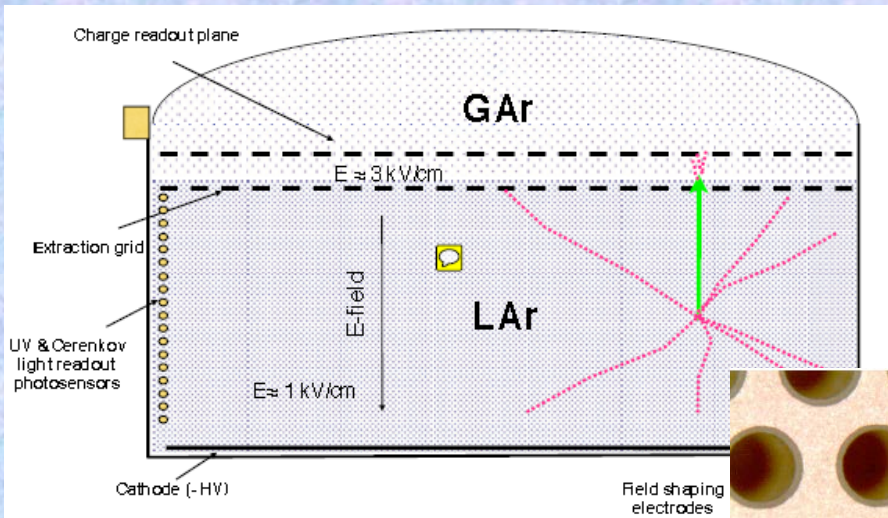
Higher performance reached with the MM + THGEM architecture (than multiple-THGEM structures)



# LEM (THGEM) Technology for Double Phase Ar-TPC

## Giant Liquid Argon Charge Imaging Experiment

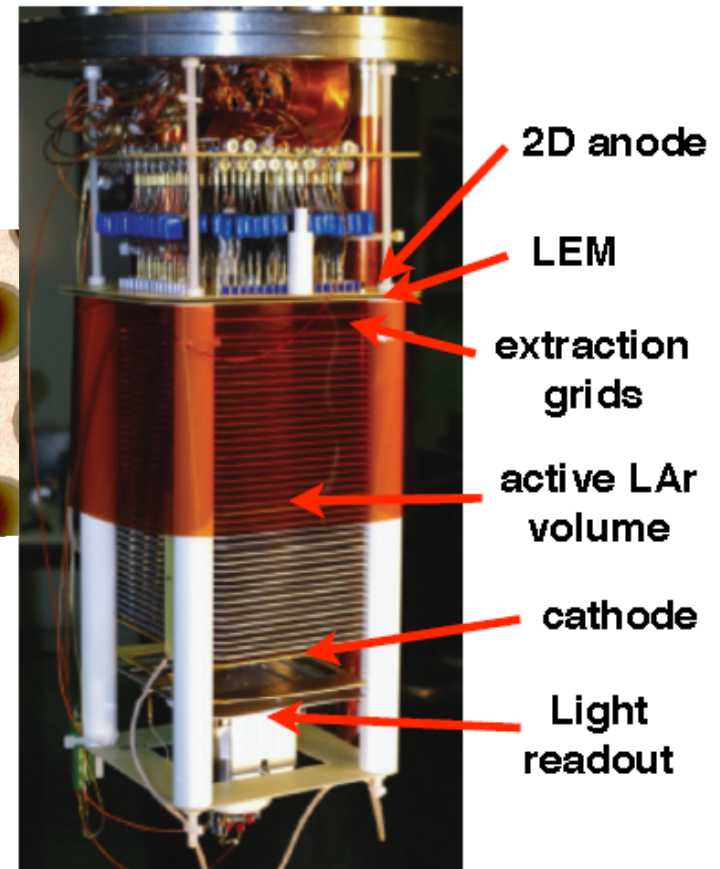
**GLACIER (hep-ph/0402110)** is a proposed giant liquid argon multi-purpose next-generation underground neutrino observatory at the 100 kton scale.



produced by CERN TS/DEM group & ELTOS company (I)

### Double-phase Ar LEM TPC

the TPC



# WG2: Generic R&D, Examples of New Ideas, Applications

## Calorimetry with MPGD:

**Resistive Micromegas for Sampling Calorimetry**  
M. Chefeldt\*, Y. Karyotakis (IN2P3/LAPP, Annecy), T. Geralis (Demokritos, Athens), M. T. H. (IN2P3, Saclay)

Calorimetry at future collider will be based on Particle Flow (PF)  
→ highly segmented calorimeters (small pads, many layers)  
Micromegas meets most of the technical and performance requirements  
...but **sparking might result from dense shower ionisation** (e.g. nuclear interactions)  
→ spark suppression by means of resistive coatings

**What resistive coating? Embedded resistor**  
Allows charge evacuation from top-to-bottom  
→ no lateral charge dispersion  
→ maintain calorimeter imaging capability

RC-constant controlled with embedded R-pattern

Star, 400 kΩ,  $\tau = 40 \mu\text{s}$     Mirror, 4 MΩ,  $\tau = 0.4 \text{ ms}$     Snake, 40 MΩ,  $\tau = 4 \text{ ms}$

Green dot = R-pad contact, blue dot = RO-pad contact

**Elba 2015**

E. Oliveri

## Fast Timing:

**MicroMegas based:**  
(initial tests March/April 2015)  
Ne-Ethane(10%)-200 micron drift+50micron Micro Bulk

**Preliminary**  
 $\approx 50\text{phe}$  preamplification  
 $\approx 50\text{phe}$   
36 picosecond rms on first try!!

**Elba 2015**  
Saclay Chamber

## New Materials (Glass GEM):

**Introduction - Glass GEM**

High field  
Radiation  
Gas  
Ionization  
Electron  
Drift  
Amplification (Factor  $\sim 10^4$ )  
Amplified electrons  
Signal formation

**02/2015**

Imaging demonstration - the bat  
Photography once, with good uniformity and fine pitch

The Latest Results of Crystallized Glass GEM, Y. Mitsui, RD51 miniweek (GDD/RD51 lab)

## Resistive Material:

### Other MPGD development using carbon sputtering

- Resistive  $\mu$ -PIC
  - New version using carbon sputtering is being tested
- Resistive GEM
  - The resistive electrodes are made by very thin (50 - 300nm) material
  - It will improve the signal gain
  - We have just made it, and it is being tested now.
  - (Scienergy + Raytech)



**08/2014 KUBEC Workshop**

A. Occhi, KUBEC Workshop 2014/8/29

## Large Area Thin Detectors:

**The  $\mu$ -RWELL performance (I)**

The prototypes have been tested with  $\text{Ar}/\text{CO}_2 = 70/30$  &  $\text{Ar}/i\text{-C}_4\text{H}_{10} = 90/10$  gas mixtures and characterized by measuring the **gas gain, rate capability and discharge in current mode**.

The devices have been **irradiated** with a collimated flux of **5.9 keV X-rays** generated by a PW2217/20 Philips Tube.

The **gain** has been measured vs potential between the top of the electrode of the gas and the resistive layer

**Elba 2015**

**GAIN UP TO  $10^4$**

$\text{Ar}/i\text{-C}_4\text{H}_{10} = 90/10$

$\mu$ -RWELL DETECTOR

## Neutrons Detection:

**In the Lab**  
 $^{241}\text{AmBe}$  source  
neutron moderated with PE  
Over  $10 \times 10 \text{ cm}^2$ :  
-  $n < 100 \text{ Hz}$   
-  $\gamma/X \gg 100 \text{ kHz}$

**50  $\mu\text{m}$  thick Cu strips**  
stop the  $\alpha/\text{Li}$   
Resolution evaluated from the sharpe edge

**B-GEM TPC**  
B10  
X-view  
Y-view

**03/2015**

European Spallation Source (ESS)

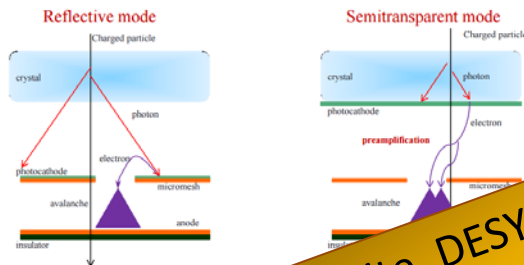


# WG2: Generic R&D, Examples of New Ideas

## FAST-TIMING MPGDs on MM concept:

### Primary ionization: photoelectrons

- Cherenkov light produced by charged particles crossing a  $\text{MgF}_2$  crystal
- Photoelectrons extracted from a photocathode (CsI)
  - ➔ Simultaneous & well localized ionization of the gas



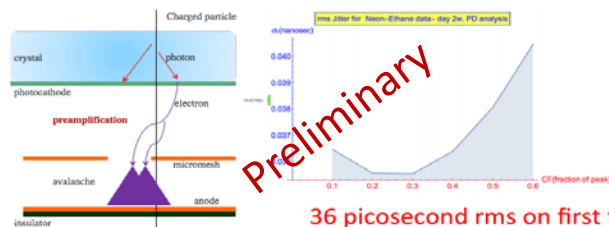
trfu Thomas Papaevangelou

15th RD51 Co

## MicroMegas b

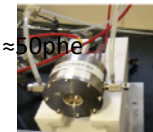
(initial tests March/April 2015)

Ne-Ethane(10%)-200 micron drift+50micron Micro Bulk



Preliminary

36 picosecond rms on first try!!



Saclay Chamber  
<-



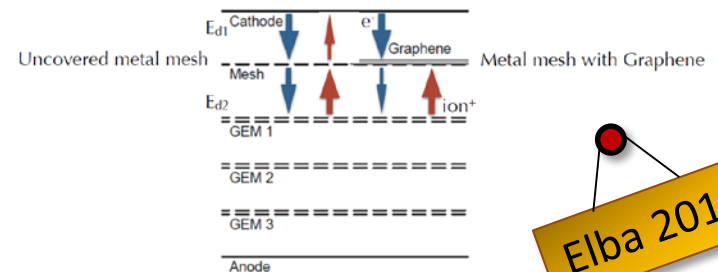
~50phe

Convert single-photoelectron time jitter  
of a few hundred picoseconds into an incident-  
particle timing response of the order of 50 ps

## Study of charge-transfer properties through graphene for gas detector applications:

### The idea

Build a suspended Graphene layer without defects  
transparent to the drifting electrons and opaque to ions  
eliminating the ion back-flow in gaseous detectors

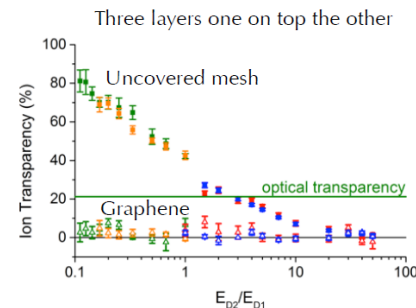


Elba 2015

It can also be used as protective layer (e.g. photocathodes)  
and to enhance secondary electron emission from materials

### The measurements

F. Resnati



Single Graphene layer:  
dominated by defects  
Triple Graphene layer:  
ion transparency drastically  
reduced, but also electrons  
do not tunnel easily

Solutions:

- 1) increase the energy of the electrons,  
i.e. different gases, larger fields (GEM holes)
- 2) improve the procedure to transfer the Graphene  
on the metal mesh to avoid ruptures of the layer

# WG2: Generic R&D, Tracking/Calorimetry Applications

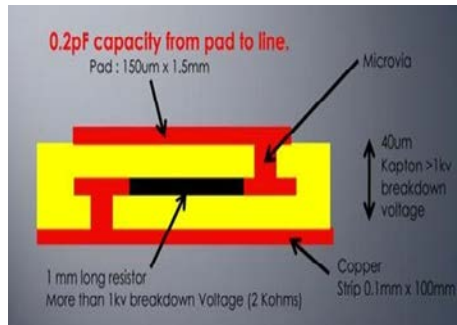
**RESISTIVE MICROMEAS:** Resistive layers are known to quench sparks at early stage

- “Horizontal” evacuation of charge → might be too slow for large areas
- Segmented R-layer to limit physical crosstalk

Optimisation:

→ reduce resistivity and evacuation time but still suppress sparking

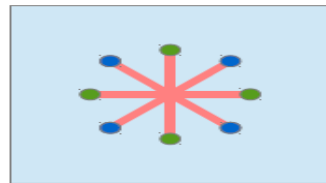
– “Vertical” evacuation of charge using buried resistors, proposed by Rui de Oliveira



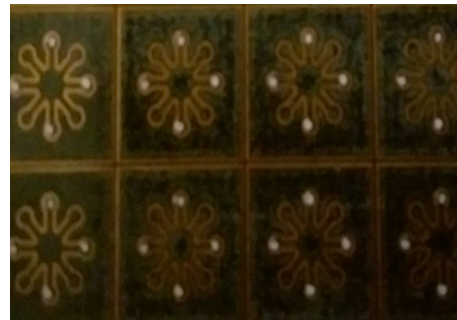
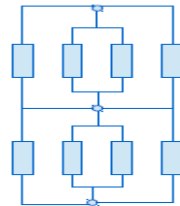
– Ongoing program:  
Vary the RC, measure the linearity (rate & dE/dx scans),  
check sparking

Work by LAPP Annecy, NCSR Demokritos, University of Athens, CEA IRFU

**Star**

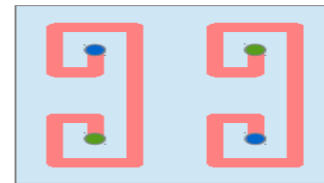


$L_{eff} \sim 0.13 \text{ cm}$   
 $R(100 \text{ k/sq}) \sim 400 \text{ kOhm}$   
 $R(1 \text{ k/sq}) \sim 4 \text{ kOhm}$



**Real R1 values:**  
**400 -750 KOhms**  
 with 100KΩ/Sq

**Mirror**

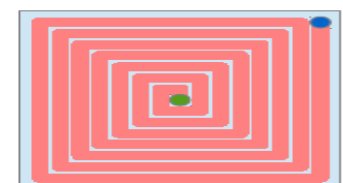


$L_{eff} \sim 1.3 \text{ cm}$   
 $R(100 \text{ k/sq}) \sim 4 \text{ MOhm}$   
 $R(1 \text{ k/sq}) \sim 40 \text{ kOhm}$

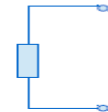


**Real R1 values:**  
**4 MOhms** with 100KΩ/Sq

**Snake**



$L \sim 13 \text{ cm}$   
 $R(100 \text{ k/sq}) \sim 40 \text{ MOhm}$   
 $R(1 \text{ k/sq}) \sim 400 \text{ kOhm}$



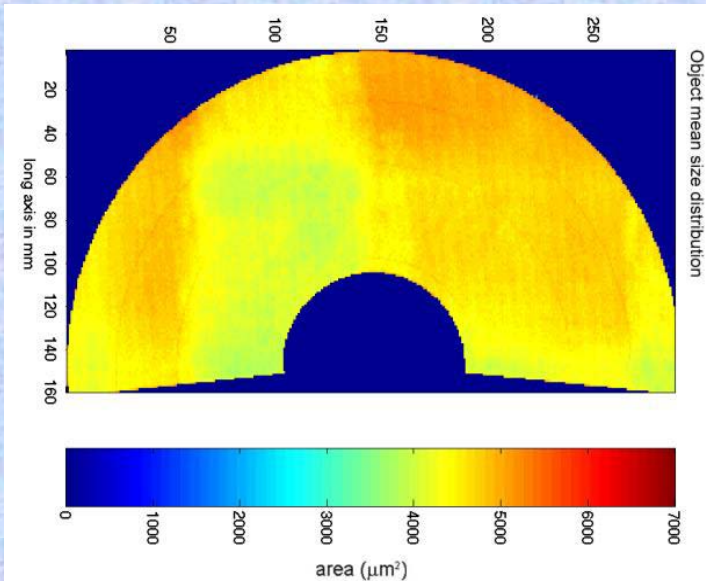
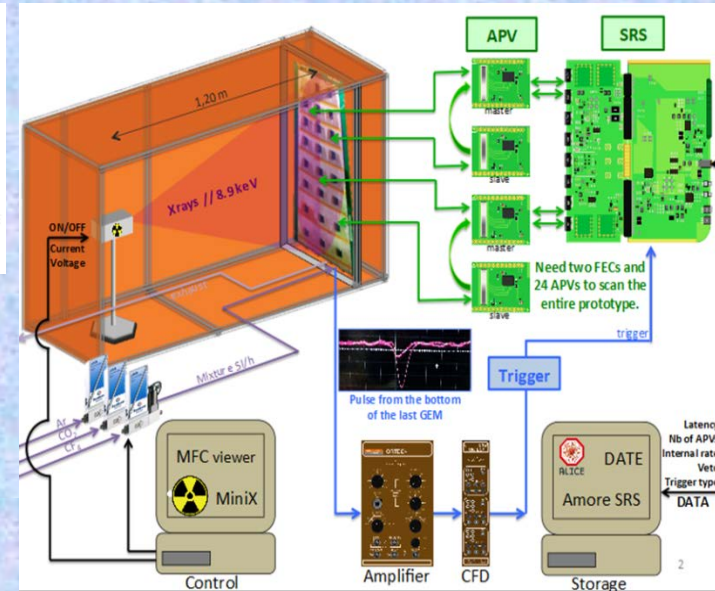
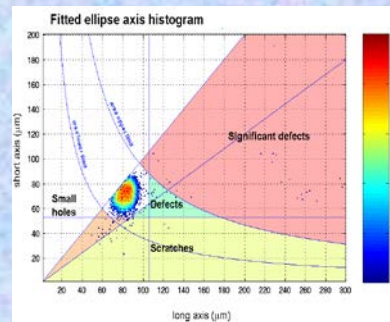
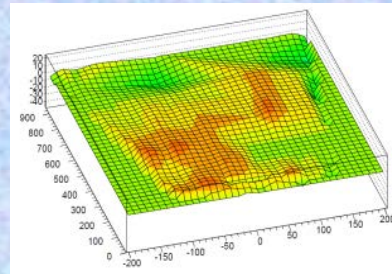
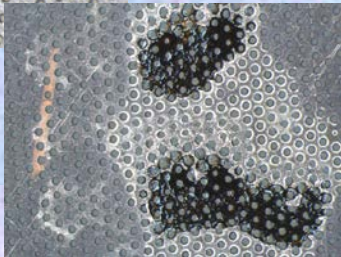
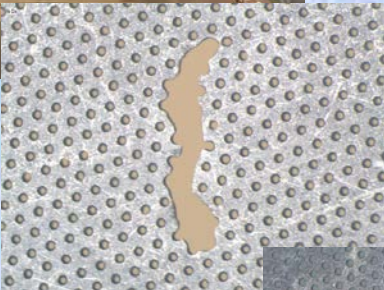
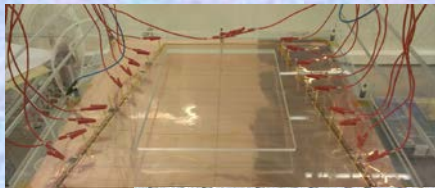
**Real R1 values:**  
**40 MOhms** With 100KΩ/Sq

M. Chefdeville, T. Gerasis



# WG2: R&D Continuation - Quality Control

- Electrical rigidity
- Hole diameter uniformity in GEM
- Gap uniformity in MicroMegas
- THGEM thickness uniformity
- Final detector calibration and characterization protocols and infrastructure



# WG2: Radiation Hardness Studies - Long Term Stability

- Classical gas detectors ageing detector
- Radiation hardness and activation of detector components
- Sustainability to neutrons and heavily ionizing particles induced discharges
- Exposure to X-Ray, Gamma, Neutron and Alpha Sources
- Monitoring infrastructure

Portable gas monitoring system for detector stability studies

→ to be used by LHCb and CMS upgrade for the muon system

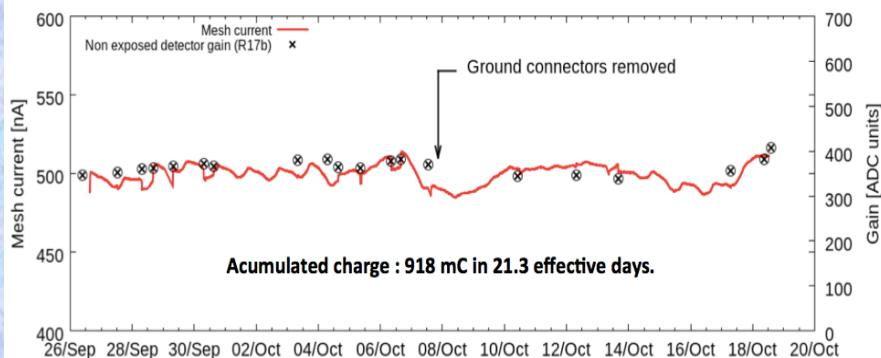


Radiation hardness of MPGDs is comparable with solid-state sensors in harsh radiation environments  
→ still, it is important to develop and validate materials with resistance to ageing and radiation damage.

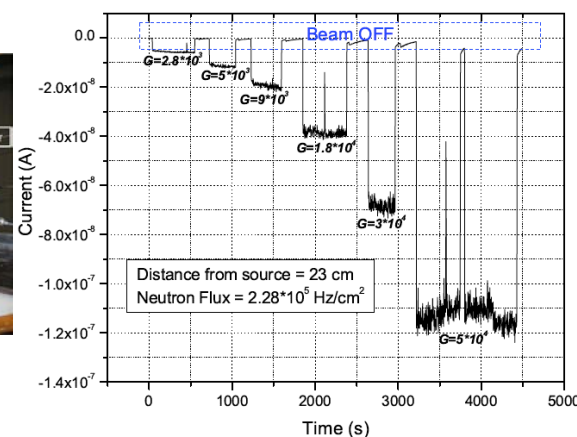
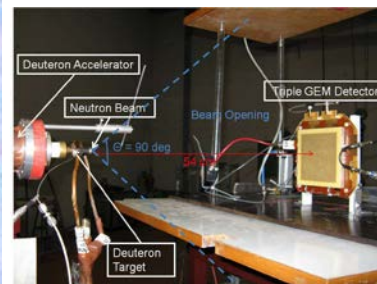
Shutter with Fe-55 sources (not shown)  
On-Detector Pressure sensor  
2 SWPC  
In-line oxygen sensor  
In-line humidity sensor  
In-line Pressure sensor  
Temperature and humidity sensors



Re stability gas  
stability performance  
under X-Ray irradiation



Discharge studies of the triple GEM detector exposed to the low energy neutron flux













## WG3: RD51 Collaboration & International Schools

## RD51 Organized Events:

**GEM & Micromegas detector design & assembly training: Lecture Session - Practical sessions**

Monday, 16 February 2009 from 08:00 to 20:00 (Europe/Zurich)  
CERN ( 513-1-024 )

<http://indico.cern.ch/event/50797/>  
<http://indico.cern.ch/event/52673/>

2009

## MPGD assembly



## MPGD simulation

RD51 Simulation School

**RD51** 19-21 January 2011  
CERN  
Europe/Zurich timezone

<http://indico.cern.ch/event/110634/>

2011

RD51 Electronics school

Charred by Leszek Ropotewski (CERN), Hans Müller (CERN), Serge Durr (Technische Universität Delft (NL)), Maksym Titov (CEA/IRFU/Centre d'étude de Saclay Gif-sur-Yvette (FR)), Maksym Titov (CEA/IRFU/Centre d'étude de Saclay Gif-sur-Yvette (FR)), Maxim Titov (CEA Saclay)

from Monday, 3 February 2014 at 08:00 to Wednesday, 5 February 2014 at 17:00

9 CERN (30-7-018 - Kjell Johnsen Auditorium)

<http://indico.cern.ch/event/283113/>

2013

# MPGD electronics



RD51 participated in XII ICFA School (Bogota, Colombia)



2013

## RD51 participated in Danube School on Instrumentation (Novi Sad Serbia)



The vitality of the MPGD community resides in the relatively large number of young scientists  
→ educational events constitute an important activity.

RD51 MPGD Lectures:  
MPGD students lectures (1 week) at the  
International Workshop on Advance  
Detectors & RD51 CM in Kolkata

# International Workshop on Advanced Detectors IWAD 2014

## & 14<sup>th</sup> RD51 Collaboration Meeting

October 27 - 31, 2014, **Co-sponsors:**  
 Kolkata - Board of Research in Nuclear Science  
 India - Department of Atomic Energy

Advanced gaseous detectors play a major role in the modern particle physics experiments. They also find wide range of applications in the areas of medical physics, astrophysics, etc. Participants regard a two-day International Workshop on Advanced Detectors (IWAD) as an opportunity to discuss the progress in the field. The October RD21 at VEC-CERN campus, Kolkata, INDIA, The workshop will be held in the same venue as the RD21. The workshop will be held in the same venue as the RD21.

**October 2014**

### Local Organizing Committee

Rajeev K. Barman	VECC
Subhas Chakrabarti	VECC
Subhas Chakrabarti (Co-Chairman)	VECC
Satya Chandra Kashyap	SNUP
Srinivas Das	RI
Anand K. Datta	VECC
(Co-Convener)	
Harpreet Kaur	SNUP
Subodh Kumar Dasgupta	SNUP
(Co-Chairman)	
Tapan K. Nayak	VECC
Ullilil M. Paul	BARC
Satyajit Saha	SNUP
Vijay Singh	VECC

### Contact

**General:** [helpdesk@rd51workshop.org](mailto:helpdesk@rd51workshop.org)  
 (Email)  
 Anand K. Datta, Convener  
 Subodh Kumar Dasgupta, Co-Convener  
 Department of Atomic Energy  
 P.O. Atomic Energy, Kolkata - 700016, India  
 Contact: +91 33 2510 16 16 (ext. 204)  
 Fax: +91 33 2510 16 19

### Registration

*(No Registration Fee for RD57 Collaboration Participants)*

Indian Participants	For 2014	For 2015
Foreign Participants	Fee: US\$ : 2000/-	Fee: US\$ : 2000/-
Indian Participants	Fee: US\$ : 500/-	Fee: US\$ : 500/-

### Workshop topics covered in the workshop

27 - 28 October, 2014

### Micro-pattern Gaseous Detectors (MPGD)

### Resistive Plate Chambers (RPC)

### Applications of advanced detectors in High Energy Physics

### Medical and other applications of advanced detectors

### International Advisory Committee

Amos Barak	WISNUS, Israel
Barbara Barlow	SNUP, India
Giuseppe Bonomi	INFN-PN, Italy
Keren K. Barak	WISNUS, Israel
Sudat Bhattacharya	SNUP, India
Blaise C. Choudhury	SNUP, India
Paul Cser	CERN, Switzerland
Maria M. Datta	INFN-PN, Italy
Walter Dorda	DESY, Germany
Kenneth G. Gonsky	CEA-Saclay, France
Heinz von der Graefen	WISNUS, Israel
Walter K. Huls	SNUP, India
Shashi K. Nayak	RI, India
Levente Rapcsanyi	CERN, Switzerland
Radi-Emul	CERN, Switzerland
Christian A. Schmidt	CERN, Switzerland
Amir Shmida	BARC, India
Dimiter K. Stanev	VECC, India
Hans Thoenes	CERN, Switzerland
Walter T. Hsu	CEA-Saclay, France
Shashi K. Nayak	INFN-PN, Italy
Vijayendra P. Singh	VECC, India
Andy White	WISNUS, Israel

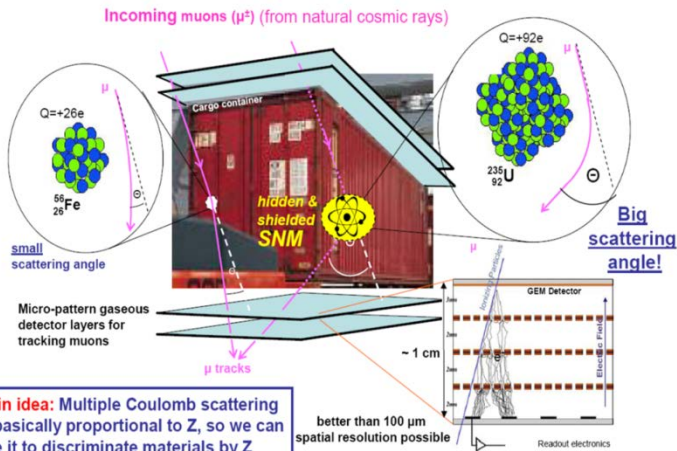
For participation in IWAD, please send one page abstract to [rd51india@cern.ch](mailto:rd51india@cern.ch) on or before **August 15, 2014**.

<http://india.cern.ch/rd51workshop>



# Spin off is important key word for the HEP labs to survive ...

## Cosmic Ray Muon Tomography Using GEMs for Homeland security



## T2DM2: Temporal Tomography Densitometric by the Measure of Muons

### Measurements on samples of small scales or large sizes



The mechanical parameters are unknown to a mass scale:  
Effective stress?  
Friction effective?  
Damage?



### Empirical methods

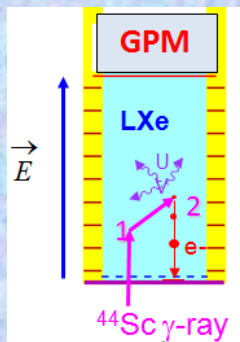
Measure:  
Mechanical parameters in small scale

Qualitative description of the rock mass (scale fracturing, alteration, hydraulic ...)

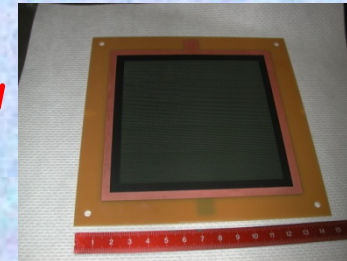
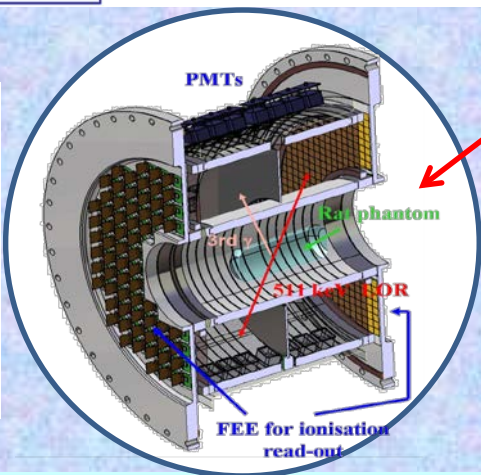
Technology

**RD51**

Technology



Liquid xenon detectors for functional medical imaging



CsI-RETGEM for UV flame detection

- ❖ Applications area will benefit from the technological developments developed by the RD51
- ❖ The responsibility for the completion of the application projects lies with the institutes themselves



# WG4: MPGD Simulation Tools



- Focus on providing techniques for calculating **electron transport in small-scale structures**
- The main difference with traditional gas-based detectors is that **the electrode scale ( $\sim 10 \mu\text{m}$ ) is comparable to the collision mean free path**

## Microscopic Tracking (Development and Maintenance of Garfield++):

Garfield++ is a collection of classes for the detailed simulation of small-scale detectors.

Garfield++ contains:

- electron and photon transport using cross sections provided by Magboltz
- ionisation processes in gases, provided by Heed and MIP
- ionisation and electron transport in semi-conductors
- field calculations from finite elements, boundary elements, analytic methods

## Simulation Improvements:

### → Transport:

- ion mobility and diffusion, measurement and modelling
- Magboltz cross sections (Ar, Xe, He, Ne;  $\text{GeH}_4$ ,  $\text{SiH}_4$ ,  $\text{C}_2\text{H}_2\text{F}_4$ ) are frequently updated in collaboration with LXCAT (<http://www.lxcat.laplace.univ-tlse.fr>)
- e-ion recombination process in Xe
- thermal motion



### → Photons:

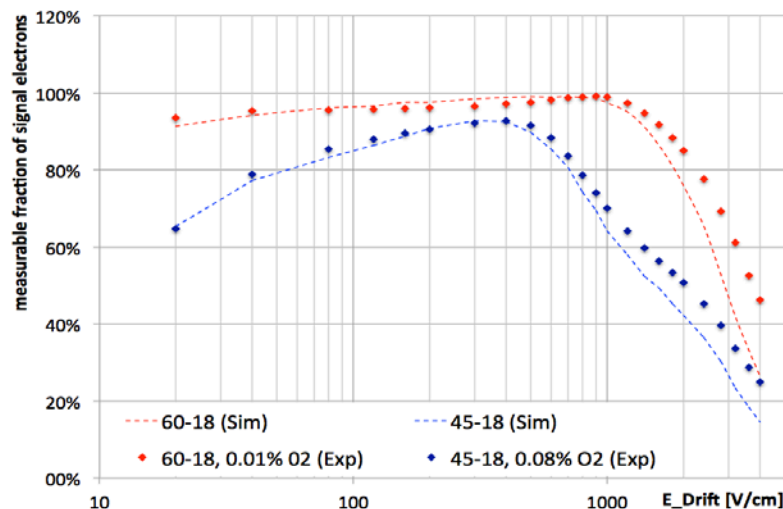
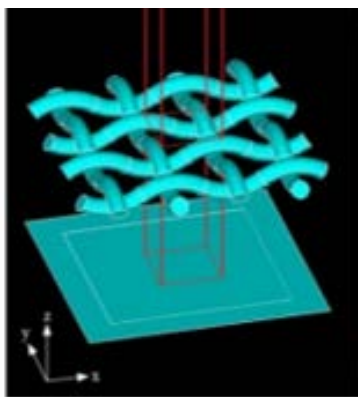
- update in UV emission
- inclusion of IR production
- photon trapping and resulting excitation transport
- photon absorption in the gas (gas feedback)
- photon absorption in and electron emission from walls (feedback)
- photo cathodes

# WG4: MPGD Strong Simulation Efforts in Very Specific Needs



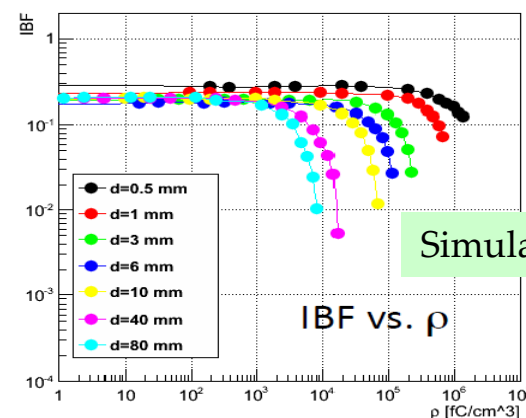
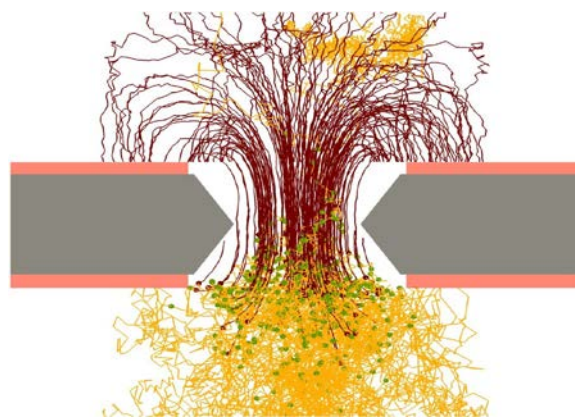
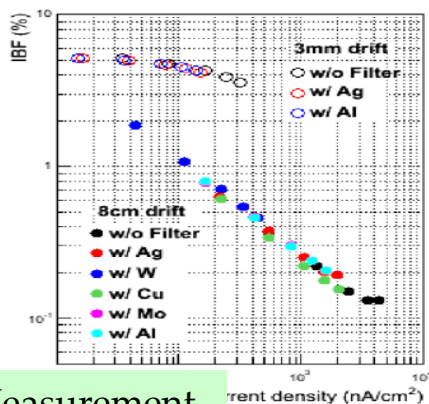
## Applications:

- GEM: multiplication process and polyimide properties; charging up effects
- MicroMegas: timing and effects of resistive layers;
  - ATLAS NSW upgrade: study of electron losses in MM with different mesh specifications



- TPC GEM: ion backflow

→ ALICE TPC upgrade: rate dependence of the Ion Back Flow in GEM



Measurement



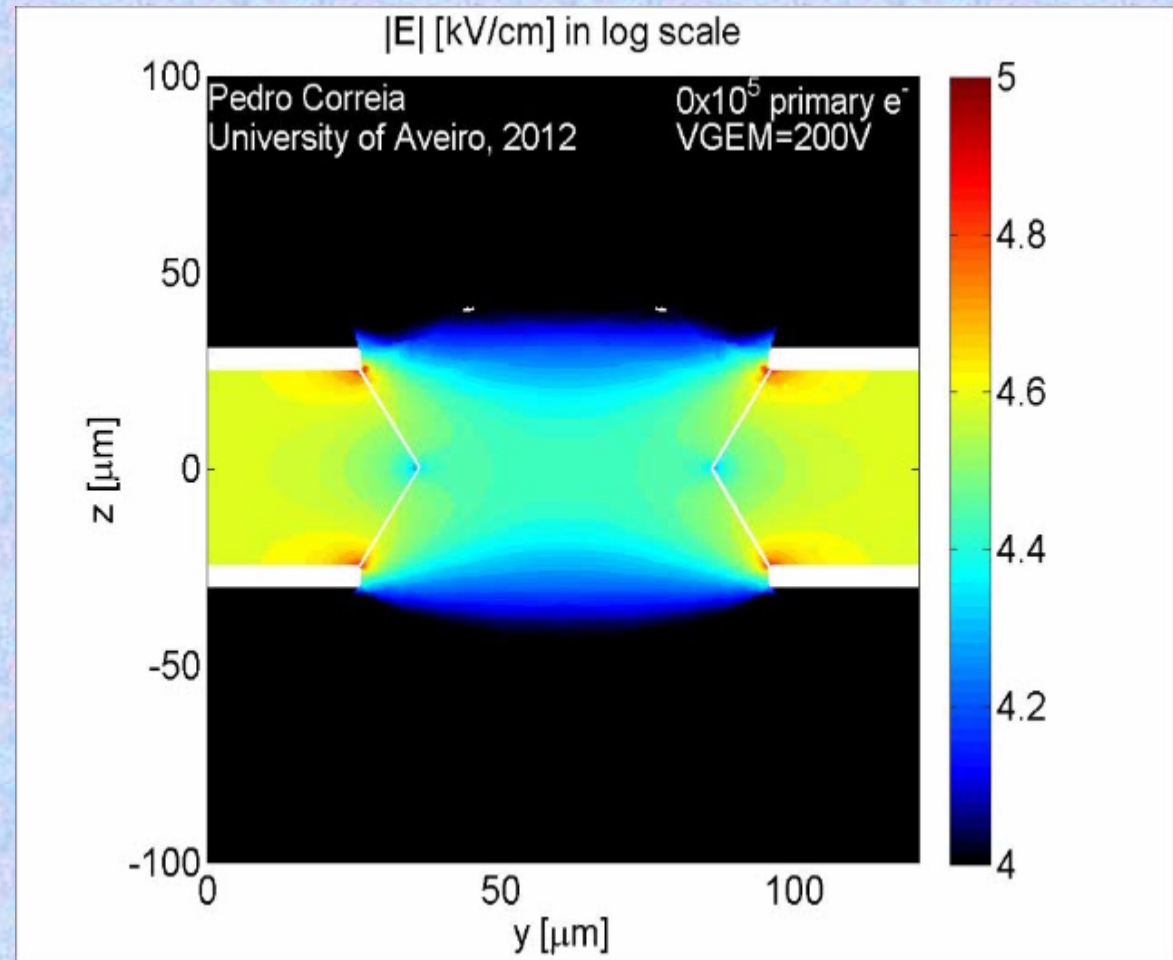
# WG4: GEM Charging-Up Effects Simulation



Electric Field Intensity during the charging-up process:

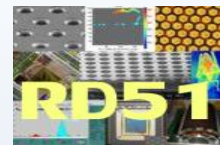
each iteration correspond to the number of primary electrons that already reached to the hole

- ANSYS: field model
- Magboltz 9.0.1: relevant cross sections of electron-matter interactions
- Garfield++: simulate electron avalanches



Charging effects are much smaller after  $(100 - 150) \cdot 10^5$  avalanches  
→ GEM gas gain stabilizes

# WG5: The RD51 Scalable Readout System (SRS) for MPGD

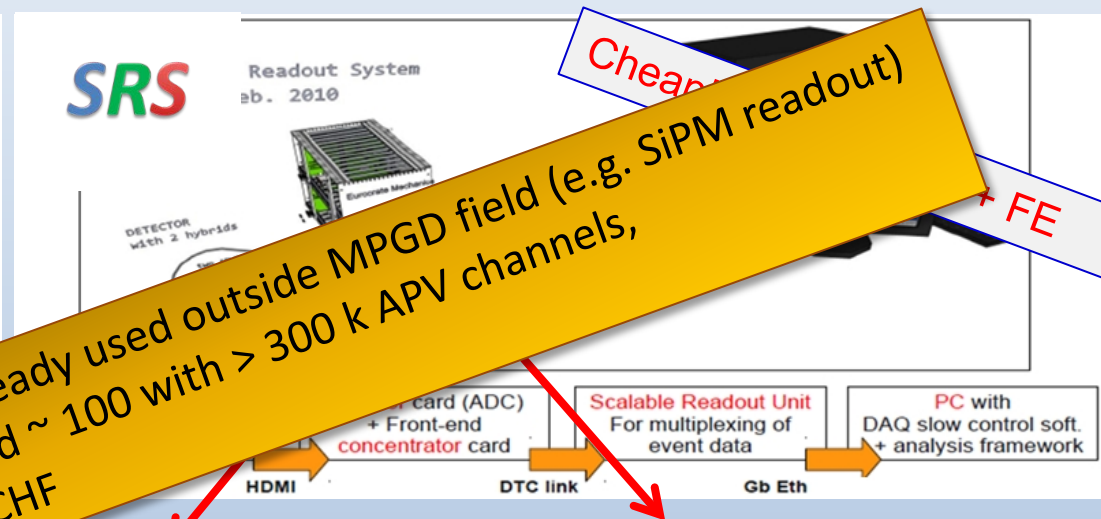


## RD51 Development / Industrialization: portable multi-channel readout system (2009-2012)

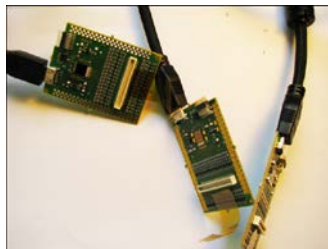
- ❖ Scalable readout architecture: from  $\sim 100$  channels up to very large LHC systems ( $> 100$  k ch.)
- ❖ Project specific part (ASIC) + common acquisition hardware and software

### Physical Overview of SRS:

- Scalability from small to large system
- Common interface for replacing the chip frontend
- Integration of proven and commercial solutions for a minimum of development
- Default availability of a very robust and supported DAQ software package



Frontend hybrids:  
based on  
APV25, VFAT, Beetle,  
VMMx and Timepix  
chips



### ADC frontend adapter for APV and Beetle chips

ADC plugs into FEC to  
make a 6U readout unit for  
up to 2048 channels



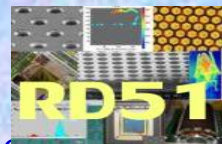
### FEC cards (common):

Virtex-5 FPGA, Gb-Ethernet, DDR buffer, NIM and LVDS pulse I/O, High speed Interface connectors to frontend adapter cards





# WG5: The RD51 Scalable Readout System (SRS) for MPGD



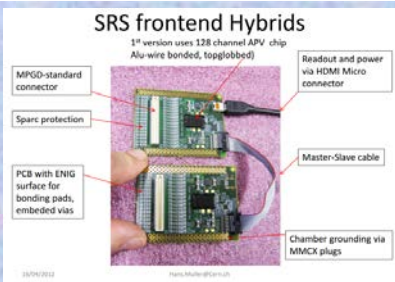
## SRS & APV25 FE chip

Worldwide use in the RD51 community (>2000 hybrids)

SRS+SiPM (NEXT TPC)

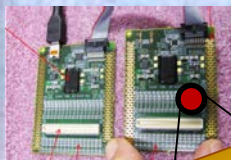


E. Oliveri



## SRS: Different System

SRS for R&D on Detectors



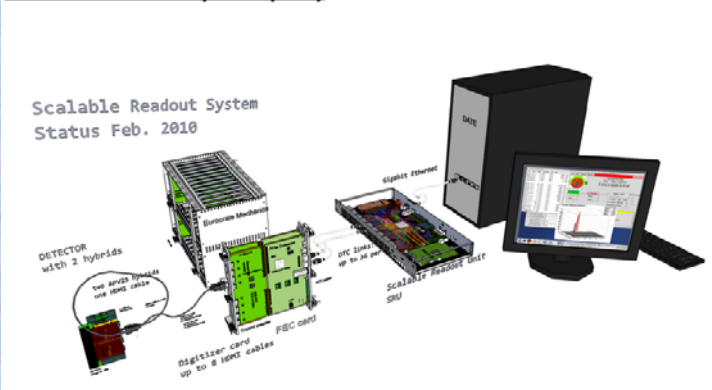
Continuously upgrading

SRS-FEC+TOTEM DAQ

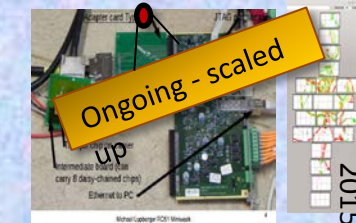


Closed to commissioning in UCS

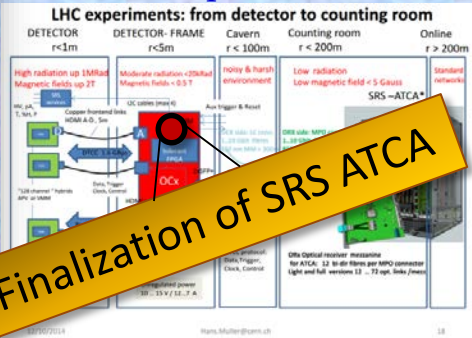
## Scalable Readout System (SRS)



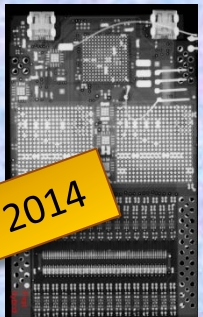
SRS+Timepix (LC-TPC) – Bonn/Desy



## SRS for experiments (ATCA)



Very appealing for the future: VMM (NSW ATLAS FE chip)



RD51 involvement since 2014

Baseline solution for RD51 SRS community.

Interest and support from ESS (European Spallation Source) and ALICE FOCAL

## SRS for spatially distributed system (optical SRS)





# WG6: MPGD Technology & Production @ CERN



## Interesting Workshop Overview Capabilities



Antonio Teixeira

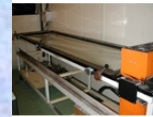
<https://indico.cern.ch/event/352483/>

•SBS tracker	GEM 600mm x 500mm
•ALICE TPC upgrade	GEM 600mm x 400mm
•CMS muon	GEM 1.2m x 450mm
•ATLAS NSW muon	Micromegas 2m x 1m
•COMPASS pixel Micromegas	GEM & Micromegas 500mm x 500mm
•BESIII	GEM 600mm x 400mm
•KLOE	GEM 700mm x 400mm
•SOLID	GEM 1.1m x 400mm
•CLAS 12	Micromegas 500mm x 500mm
•LSBB (geoscience)	Micromegas 1m x 500mm
•Prad	GEM 1.5m x 55cm
•CBM	GEM 1m x 450mm
•ASACUSA	Micromegas

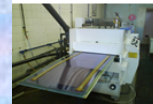
## MPGD Projects....

•Most of them are still at the R&D phase but some are already in production:	
•ATLAS NSW	1300 m <sup>2</sup>
•SBS Tracker	100 GEMs
•ALICE TPC upgrade	350 GEMs
•COMPASS pixel Micromegas	20 GEM + Micromegas
•BESIII	15 GEM
•CLAS 12	30 Micromegas
•CMS	450 GEM

## New Capabilities....



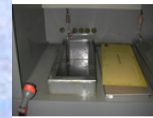
UV exposure unit limited to 2m x 0.6m  
→ 2.2m x 1.4m



Resist developer limited to 0.6m width → 1.2m



Resist stripper  
Copper etcher  
Dryer



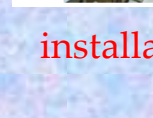
GEM electro etch limited to 1m → 2m



GEM polyimide etch limited to 1m → 2m



Ovens limited to 1.5m x 0.6m → 2.2m x 1.4m



Laminator limited to 0.6m width → 1.2m

installation of the new infrastructure (to fabricate 2x1m<sup>2</sup>  
Bulk MM & 2x0.5m<sup>2</sup> GEM) COMPLETED

Construction of the new  
workshop's building:

Start : beginning 2012  
End: end 2017



CERN Building 107  
Basis of Design



# WG6: MPGD Technology Industrialization



**Technology Industrialization** → transfer “know-how” from CERN workshop to industrial partners

## **GEM Technology** (contacts):

- Mecharonix (Korea, Seoul)
- Tech-ETCH (USA, Boston)
- Scienergy (Japan, Tokyo)
- TECHTRA (Poland, Wroclaw)

## **GEM Licenses signed by:**

- ✓ Mecharonix, 21/05/2013
- ✓ TECH-ETCH, 06/03/2013
- ✓ China IAE, 10/01/2012
- ✓ SciEnergy, 06/04/2009
- ✓ Techtra, 09/02/2009
- ✓ CDT, 25/08/2008
- ✓ PGE, 09/07/2007

## **MicroMegas Technology**(contacts):

- ELTOS S.p.A. (Italy)
- TRIANGLE LABS(USA, Nevada)
- SOMACIS (Italy, Castelfidardo)
- ELVIA (France, CHOLET)

## **THGEM Technology** (contacts):

- ELTOS S.p.A. (Italy),
- PRINT ELECTRONICS



## **GEM Industrialization Status (June 2015):**

### **TECH-ETCH**

- Single Mask process fully understood. Many 10cm x 10cm produced and characterized.
- 40cm x 40cm GEM successfully produced
- CMS GE1/1 size of 1m x 0.5m started

### **TECHTRA**

- Production Line Operational
- Stable process for 10cm x 10cm
- Single Mask process completely understood – 10cm x 10cm produced
- 30cm x 30cm Single Mask Produced

### **MECHARONICS**

- 10cm x 10cm double mask produced and tested
- 30cm x 30cm double mask under evaluation @ CERN
- CMS GE1/1 size of 1m x 0.5m started

## **Micromegas Industrialization Status (June 2015):**

### **ELVIA**

- Bulk Micromegas detectors are routinely produced with sizes up to 50cm x 50 cm.
- Contract for ATLAS NSW module-0 signed
- Tendering process for full production ongoing

### **ELTOS**

- Many small size bulk Micromegas detectors have been produced.
- Contract for ATLAS NSW module-0 signed
- Tendering process for full production ongoing

**ATLAS NSW upgrade → will first detector mass-produced in industry**  
**using a large high-granularity Micromegas:**  
**det. area ~1300 m<sup>2</sup> divided into 2 m x 0.5 m<sup>2</sup> units**

# WG7: PH-GDD Laboratory ... Laboratory available for RD51 Collaboration



Permanent installations (Today): ALICE, ATLAS, ESS

CMS moved roughly two years ago to TIFF, access to the lab for specific measurements

More than 15/20 groups per year coming to perform measurements

E. Oliveri

Clean Rooms

Mechanical and Electronic Workshop

Technical support

MPGD Detectors

Gas system and services

Readout electronics (std and custom RD51 SRS&APV)

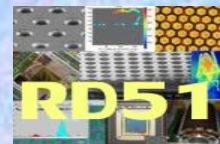
Radioactive Sources

Interface with CERN services  
(RP, gas, metrology, irradiation facilities,...)

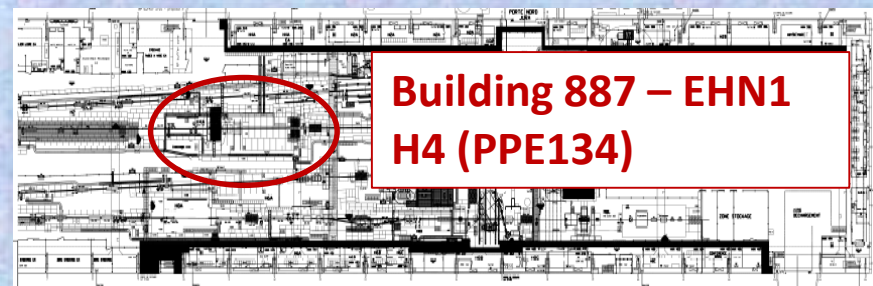
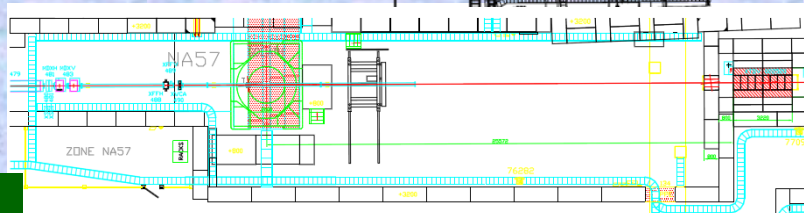
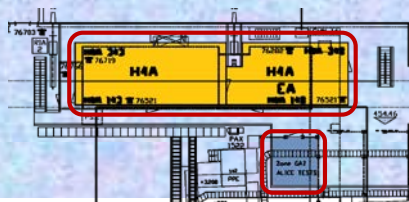




# WG7:Semi-Permanent Test Beam Infrastructure in the SPS line



Three periods of two weeks each per year  
About fifteen-twenty users per year



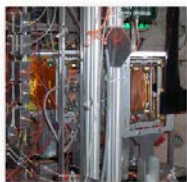
Building 887 – EHN1  
H4 (PPE134)

Goliath Magnet (1.4 T)  
→ Ship Experiment?

E. Oliveri

## Rd51 trackers

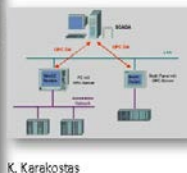
- Triple GEM Tracker
  - XY strips readout, 400um pitch
  - 10x10 cm<sup>2</sup>
  - APV (VFAT2)
  - DAQ&FE: SRS/APV (TURBO/VFAT)



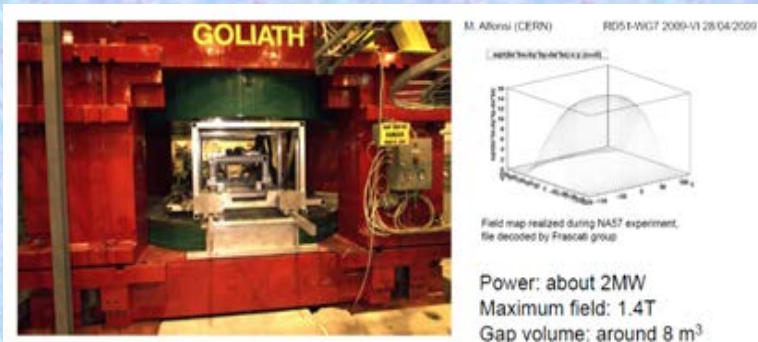
- Resistive  $\mu$ megas tracker
  - XY strips readout, 250um pitch
  - 9x9 cm<sup>2</sup>
  - APV
  - DAQ&FE: SRS/APV



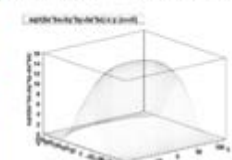
## Slow Control System (HV/LV)



K. Karakostas



M. Azzurri (CERN) RD51-WG7 2009-V1 28/04/2009



Field map realized during NA57 experiment, file decoded by Frascati group

Power: about 2MW  
Maximum field: 1.4T  
Gap volume: around 8 m<sup>3</sup>

## 2014 test Beam

December 2014



CMS (GEM)



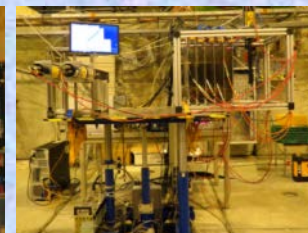
WIS/A/C(WELL, THGEM)



ATLAS NSW (mm)



BESS III & SHIP (GEM)



LAPP/DEM/IRFU(mm)



ALICE TPC (GEM and mm)

2008-2015: ~ 40 RD51 groups participated (2015 test Beam: May-June, July, October)



# IWAD conference & RD51 Collaboration Meeting

[illegible][illegible]

October 2015 (Trieste)

## TOPICS

NEW DEVELOPMENTS IN MPDGS  
PRODUCTION TECHNIQUES  
MATERIAL AND AGEING TESTS  
MPGD DETECTOR PHYSICS

SIMULATION AND SOFTWARE  
ELECTRONICS  
APPLICATIONS

# MPGD conferences & RD51CM

2009

[illegible]

2011



3rd International Conference on Micro Pattern Gaseous Detectors

# MPGD2013

01-04 July 2013 - Zauggen (Spain)  
 1st-5th Collaboration Meetings on July 5-6

**Topics are:**

- New developments in MPGDs
- Production techniques
- Performance tests
- MPGD detector applications: simulation and software
- Electronics
- Applications

1st-5th Collaboration Meetings	01-04 July 2013	05-06 July 2013
1. Welcome 2. Introduction 3. LHC and CMS 4. ATLAS 5. CMS 6. CMS 7. CMS 8. CMS 9. CMS 10. CMS 11. CMS 12. CMS 13. CMS 14. CMS 15. CMS 16. CMS 17. CMS 18. CMS 19. CMS 20. CMS 21. CMS 22. CMS 23. CMS 24. CMS 25. CMS 26. CMS 27. CMS 28. CMS 29. CMS 30. CMS 31. CMS 32. CMS 33. CMS 34. CMS 35. CMS 36. CMS 37. CMS 38. CMS 39. CMS 40. CMS 41. CMS 42. CMS 43. CMS 44. CMS 45. CMS 46. CMS 47. CMS 48. CMS 49. CMS 50. CMS 51. CMS 52. CMS 53. CMS 54. CMS 55. CMS 56. CMS 57. CMS 58. CMS 59. CMS 60. CMS 61. CMS 62. CMS 63. CMS 64. CMS 65. CMS 66. CMS 67. CMS 68. CMS 69. CMS 70. CMS 71. CMS 72. CMS 73. CMS 74. CMS 75. CMS 76. CMS 77. CMS 78. CMS 79. CMS 80. CMS 81. CMS 82. CMS 83. CMS 84. CMS 85. CMS 86. CMS 87. CMS 88. CMS 89. CMS 90. CMS 91. CMS 92. CMS 93. CMS 94. CMS 95. CMS 96. CMS 97. CMS 98. CMS 99. CMS 100. CMS 101. CMS 102. CMS 103. CMS 104. CMS 105. CMS 106. CMS 107. CMS 108. CMS 109. CMS 110. CMS 111. CMS 112. CMS 113. CMS 114. CMS 115. CMS 116. CMS 117. CMS 118. CMS 119. CMS 120. CMS 121. CMS 122. CMS 123. CMS 124. CMS 125. CMS 126. CMS 127. CMS 128. CMS 129. CMS 130. CMS 131. CMS 132. CMS 133. CMS 134. CMS 135. CMS 136. CMS 137. CMS 138. CMS 139. CMS 140. CMS 141. CMS 142. CMS 143. CMS 144. CMS 145. CMS 146. CMS 147. CMS 148. CMS 149. CMS 150. CMS 151. CMS 152. CMS 153. CMS 154. CMS 155. CMS 156. CMS 157. CMS 158. CMS 159. CMS 160. CMS 161. CMS 162. CMS 163. CMS 164. CMS 165. CMS 166. CMS 167. CMS 168. CMS 169. CMS 170. CMS 171. CMS 172. CMS 173. CMS 174. CMS 175. CMS 176. CMS 177. CMS 178. CMS 179. CMS 180. CMS 181. CMS 182. CMS 183. CMS 184. CMS 185. CMS 186. CMS 187. CMS 188. CMS 189. CMS 190. CMS 191. CMS 192. CMS 193. CMS 194. CMS 195. CMS 196. CMS 197. CMS 198. CMS 199. CMS 200. CMS 201. CMS 202. CMS 203. CMS 204. CMS 205. CMS 206. CMS 207. CMS 208. CMS 209. CMS 210. CMS 211. CMS 212. CMS 213. CMS 214. CMS 215. CMS 216. CMS 217. CMS 218. CMS 219. CMS 220. CMS 221. CMS 222. CMS 223. CMS 224. CMS 225. CMS 226. CMS 227. CMS 228. CMS 229. CMS 230. CMS 231. CMS 232. CMS 233. CMS 234. CMS 235. CMS 236. CMS 237. CMS 238. CMS 239. CMS 240. CMS 241. CMS 242. CMS 243. CMS 244. CMS 245. CMS 246. CMS 247. CMS 248. CMS 249. CMS 250. CMS 251. CMS 252. CMS 253. CMS 254. CMS 255. CMS 256. CMS 257. CMS 258. CMS 259. CMS 260. CMS 261. CMS 262. CMS 263. CMS 264. CMS 265. CMS 266. CMS 267. CMS 268. CMS 269. CMS 270. CMS 271. CMS 272. CMS 273. CMS 274. CMS 275. CMS 276. CMS 277. CMS 278. CMS 279. CMS 280. CMS 281. CMS 282. CMS 283. CMS 284. CMS 285. CMS 286. CMS 287. CMS 288. CMS 289. CMS 290. CMS 291. CMS 292. CMS 293. CMS 294. CMS 295. CMS 296. CMS 297. CMS 298. CMS 299. CMS 300. CMS 301. CMS 302. CMS 303. CMS 304. CMS 305. CMS 306. CMS 307. CMS 308. CMS 309. CMS 310. CMS 311. CMS 312. CMS 313. CMS 314. CMS 315. CMS 316. CMS 317. CMS 318. CMS 319. CMS 320. CMS 321. CMS 322. CMS 323. CMS 324. CMS 325. CMS 326. CMS 327. CMS 328. CMS 329. CMS 330. CMS 331. CMS 332. CMS 333. CMS 334. CMS 335. CMS 336. CMS 337. CMS 338. CMS 339. CMS 340. CMS 341. CMS 342. CMS 343. CMS 344. CMS 345. CMS 346. CMS 347. CMS 348. CMS 349. CMS 350. CMS 351. CMS 352. CMS 353. CMS 354. CMS 355. CMS 356. CMS 357. CMS 358. CMS 359. CMS 360. CMS 361. CMS 362. CMS 363. CMS 364. CMS 365. CMS 366. CMS 367. CMS 368. CMS 369. CMS 370. CMS 371. CMS 372. CMS 373. CMS 374. CMS 375. CMS 376. CMS 377. CMS 378. CMS 379. CMS 380. CMS 381. CMS 382. CMS 383. CMS 384. CMS 385. CMS 386. CMS 387. CMS 388. CMS 389. CMS 390. CMS 391. CMS 392. CMS 393. CMS 		

2013

4TH INTERNATIONAL CONFERENCE ON MICRO PATTERN GASEOUS DETECTORS - MPGD2015 - TRIESTE, 12-15 OCTOBER 2015  
RD51 COLLABORATION MEETING ON 16-17 OCTOBER 2015

INFN  
Istituto Nazionale  
di Fisica Nucleare  
Sezione di Trieste

MPGD 2015

October 2015 (Trieste)

TOPICS

NEW DEVELOPMENTS IN MPDGs  
PRODUCTION TECHNIQUES  
MATERIAL AND AGEING TESTS  
MPGD DETECTOR PHYSICS

SIMULATION AND SOFTWARE  
ELECTRONICS  
APPLICATIONS

INTERNATIONAL ORGANIZING COMMITTEE  
ALESSANDRO CARDINI (INFN, TRIESTE)  
KLAUS DESCH (BONNEN, GERMANY)  
THEODOROS (ATHENS, GREECE)

MPGD 2015  
4TH INTERNATIONAL CONFERENCE ON MICRO  
PATTERN GASEOUS DETECTORS  
(TRIESTE, 12-15 OCTOBER 2015)  
RD51 COLLABORATION MEETING (16-17 OCTOBER 2015)

MPGD 2015 & RD51 Collaboration meeting

12-17 October 2015 Trieste - Italy  
Europe/Rome time zone

[HTTP://MPGD2015.TS.INFN.IT](http://mpgd2015.ts.infn.it)

MPGD@TS.INFN.IT

[HTTP://MPGD2015.TS.INFN.IT](http://MPGD2015.TS.INFN.IT)

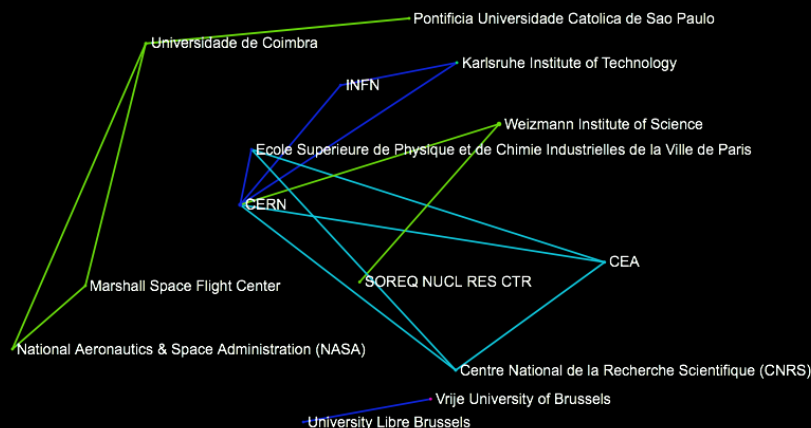
MPGD@TS.INFN.IT



# RD51 and the Rise of Micro-Pattern Gas Detectors



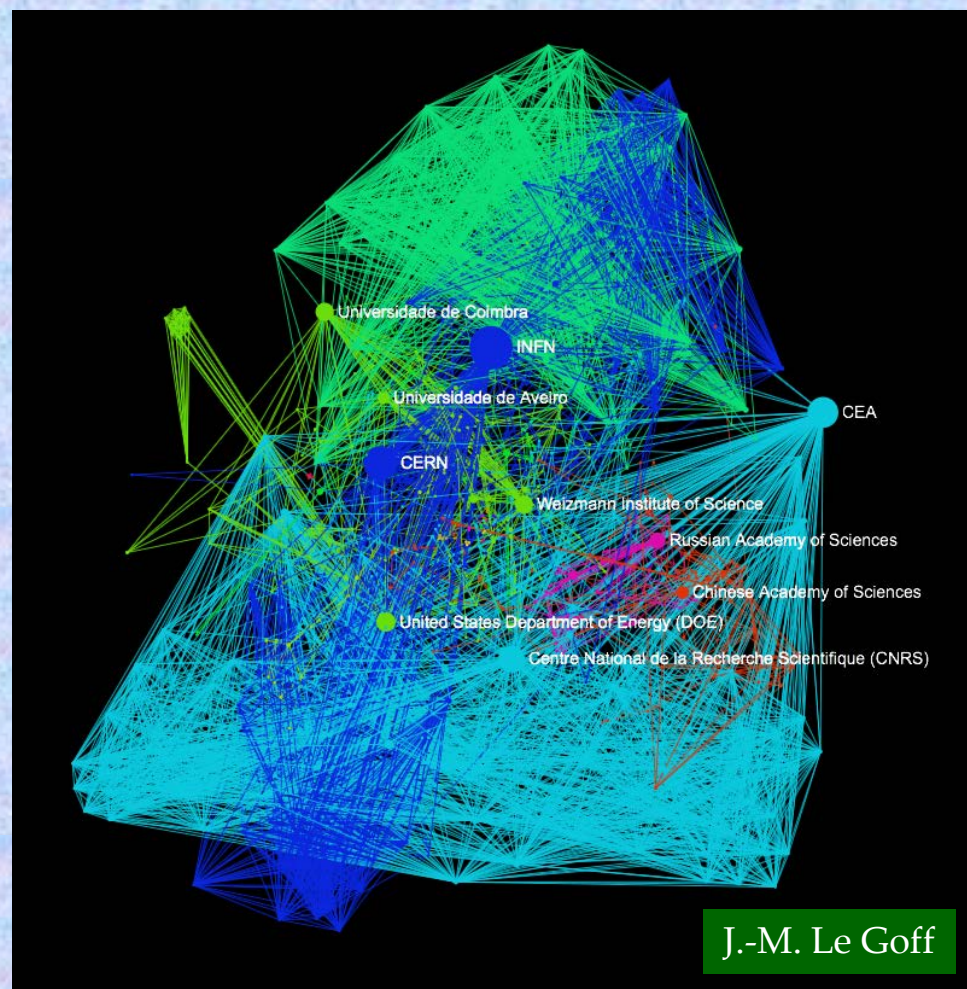
A fundamental boost is offered by RD51:  
from isolate MPGD developers to a world-  
wide net



A combined map of organizations working  
with MPGDs built with collaboration-spotting  
software developed at CERN

→ huge growth in interest in the MPGD  
technologies

Collaboration Spotting Software:  
<http://collspotting.web.cern.ch/>



J.-M. Le Goff

Map: **RD51**

Current year:	1998
Organisations:	40/717
Clusters:	5
Publications:	35/1059

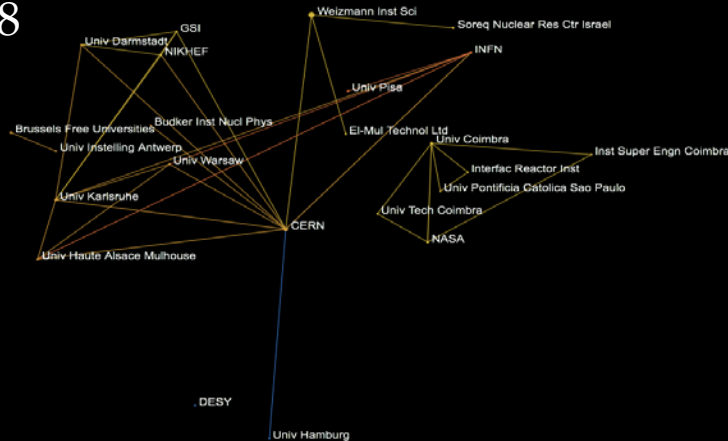
Map: **RD51**

Current year:	2015
Organisations:	717
Clusters:	12
Publications:	1059

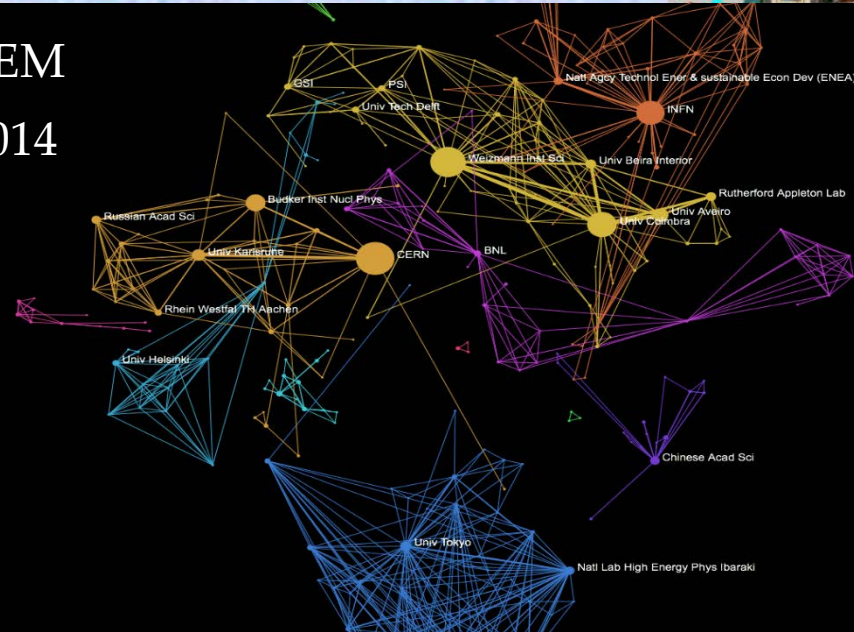
# RD51 and the Rise of Micro-Pattern Gas Detectors



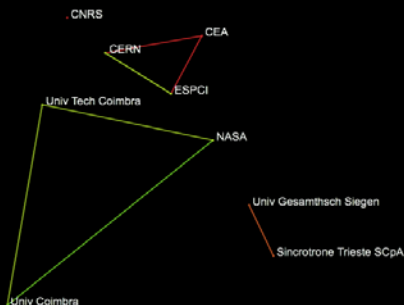
GEM  
1998



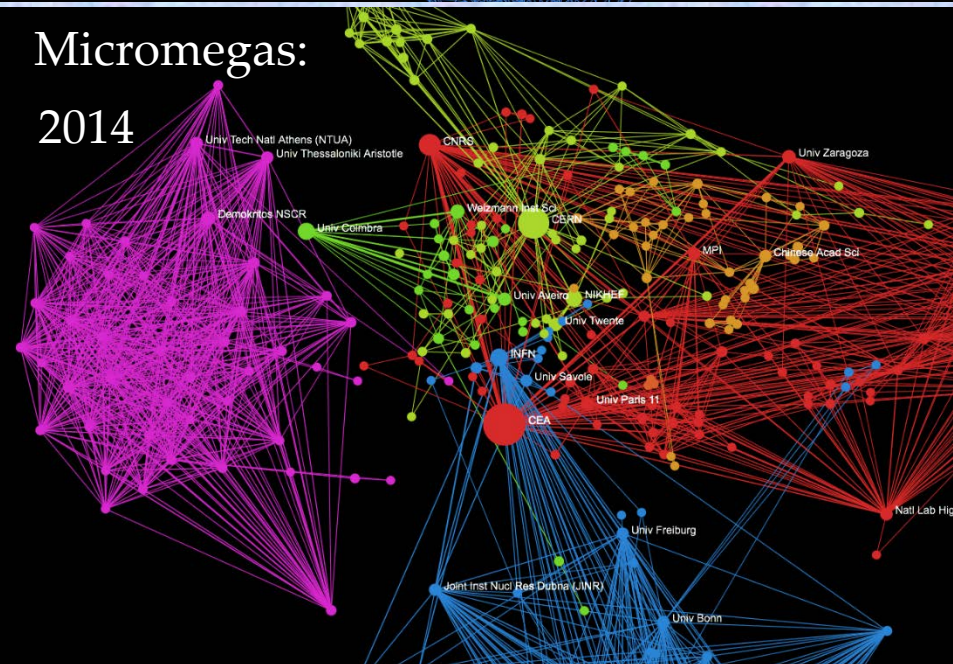
GEM  
2014



Micromegas:  
1998



Micromegas:  
2014



J.-M. Le Goff



# RD51 and the rise of micro-pattern gas detectors

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

Improvements in detector technology often come from capitalizing on industrial progress. Over the past two decades, advances in photolithography, microelectronics and printed circuits have opened the way for the production of micro-structured gas-amplification devices. By 2008, interest in the development and use of the novel micro-pattern gaseous detector (MPGD) technologies led to the establishment at CERN of the RD51 collaboration. Originally created for a five-year term, RD51 was later prolonged for another five years beyond 2013. While many of the MPGD technologies were introduced before RD51 was founded (figure 1), with more techniques becoming available or affordable, new detection concepts are still being introduced, and existing ones are substantially improved.

In the late 1980s, the development of the micro-strip gas chamber (MSGC) created great interest because of its intrinsic rate-capability, which was orders of magnitude higher than in wire chambers, and its position resolution of a few tens of micrometres at particle fluxes exceeding about  $1 \text{ MHz/mm}^2$ . Developed for projects at high-luminosity colliders, MSGCs promised to fill a gap between the high-performance but expensive solid-state detectors, and cheap but rate-limited traditional wire chambers. However, detailed studies of their long-term behaviour at high rates and in hadron beams revealed two possible weaknesses of the MSGC technology: the formation of deposits on the electrodes, affecting gain and performance ("ageing effects"), and spark-induced damage to electrodes in the presence of highly ionizing particles.

These initial ideas have since led to more robust MPGD structures, in general using modern photolithographic processes on thin insulating supports. In particular, ease of manufacturing, operational stability and superior performances for charged-particle tracking, muon detection and triggering have given rise to two main designs: the gas electron-multiplier (GEM) and micro-mesh gaseous structure (Micromegas). By using a pitch size of a few hundred micrometres, both devices exhibit intrinsic high-rate capability ( $> 1 \text{ MHz/mm}^2$ ), excellent spatial and multi-track resolution (around  $30 \mu\text{m}$  and  $500 \mu\text{m}$ , respectively), and time resolution for single photoelectrons in the sub-nanosecond range.

Coupling the microelectronics industry and advanced PCB technology has been important for the development of gas detectors with increasingly smaller pitch size. An elegant example is the use of a CMOS pixel ASIC, assembled directly below the GEM or Micromegas amplification structure. Modern "wafer post-processing technology" allows for the integration of a Micromegas grid directly on top of a Medipix or Timepix chip, thus forming

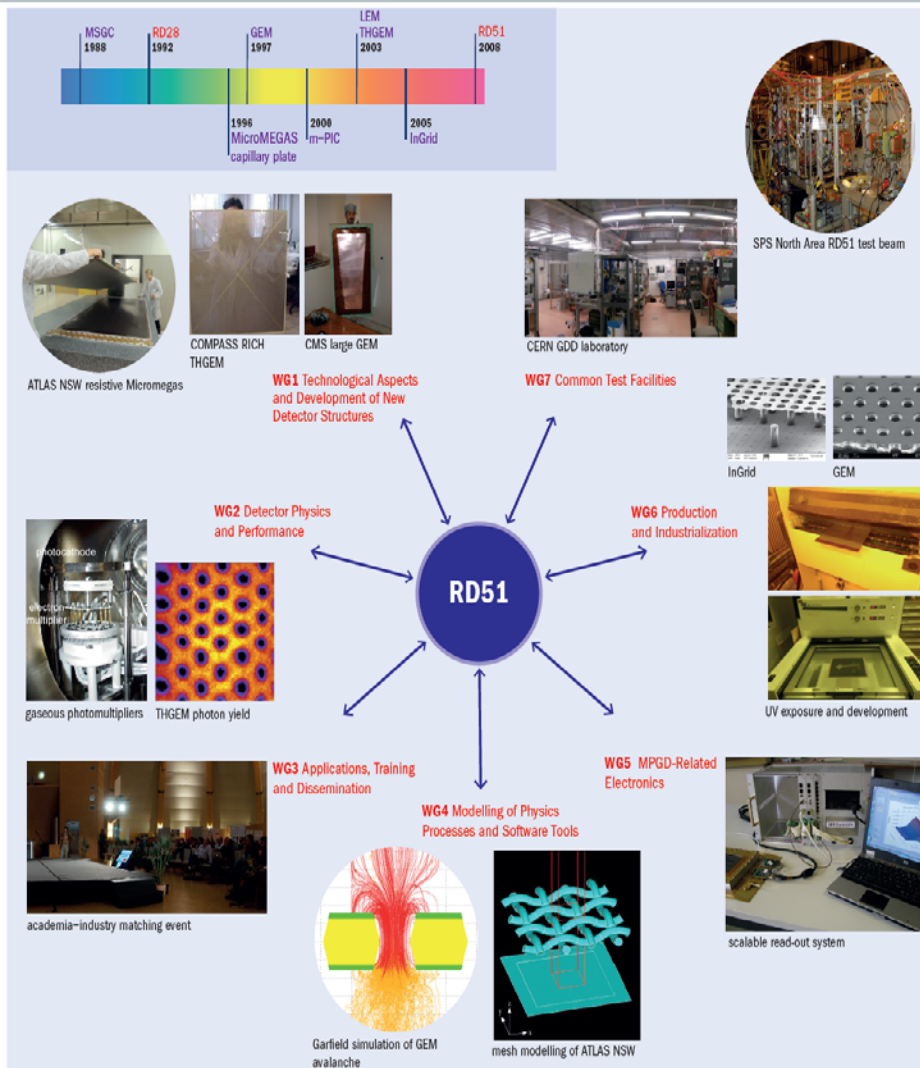


Fig.1. The seven working groups of RD51, with illustrations of just a few examples of the different kinds of work involved. Top left: the 20-year pre-history of RD51. (Image credits: RD51 Collaboration.)

integrated read-out of a gaseous detector (InGrid). Using this approach, MPGD-based detectors can reach the level of integration, compactness and resolving power typical of solid-state pixel devices. For applications requiring imaging detectors with large-area coverage and moderate spatial resolution (e.g. ring-imaging Cherenkov (RICH) counters), coarser macro-patterned structures offer an interesting economic solution with relatively low mass and easy construction – thanks to the intrinsic robustness of the PCB electrodes. Such detectors are the thick GEM (THGEM), large electron multiplier (LEM), patterned resistive thick GEM (RETGEM) and the resistive-plate WELL (RPWELL).

## RD51 and its working groups

The main objective of RD51 is to advance the technological development and application of MPGDs. While a number of activities have emerged related to the LHC upgrade, most importantly, RD51 serves as an access point to MPGD "know-how" for the world-wide community – a platform for sharing information, results and experience – and optimizes the cost of R&D through the sharing of resources and the creation of common projects and infrastructure. All partners are already pursuing either basic- or application-oriented R&D involving MPGD concepts. Figure 1 shows the organization of seven Working Groups (WG) that cover all of the relevant aspects of MPGD-related R&D.

**WG1 Technological Aspects and Development of New Detector Structures.** The objectives of WG1 are to improve the performance of existing detector structures, optimize fabrication methods, and develop new multiplier geometries and techniques. One of the most prominent activities is the development of large-area GEM, Micromegas and THGEM detectors. Only one decade ago, the largest MPGDs were around  $40 \times 40 \text{ cm}^2$ , limited by existing tools and materials. A big step towards the industrial manufacturing of MPGDs with a size around a square metre came with new fabrication methods – the single-mask GEM, "bulk" Micromegas and the novel Micromegas construction scheme with a "floating mesh". While in the "bulk" Micromegas, the metallic mesh is integrated into the PCB read-out. In the latter case, the mesh is integrated in the panel containing drift electrodes and placed on pillars when the chamber is closed. The single-mask GEM technique overcomes the cumbersome practice of alignment of two masks between top and bottom films, which limits the achievable lateral size to 50 cm. This technology, together with the novel "self-stretching technique" for assembling GEMs without glue and spacers, simplifies the fabrication process to such an extent that, especially for large-volume production, the cost per unit area drops by orders of magnitude. >

# Gaseous Tracking: Detector-Electronics Integration Trends

Wire Chambers, TPC, RPC → MPGD (GEM, Micromegas) → InGrid (3D)

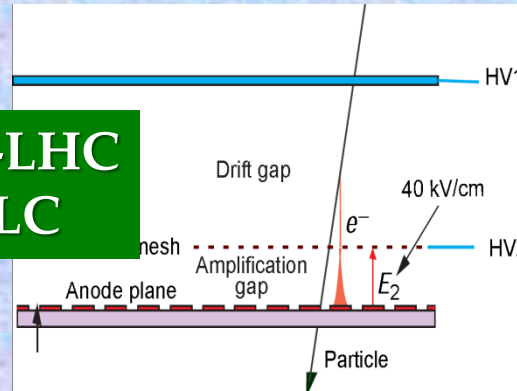
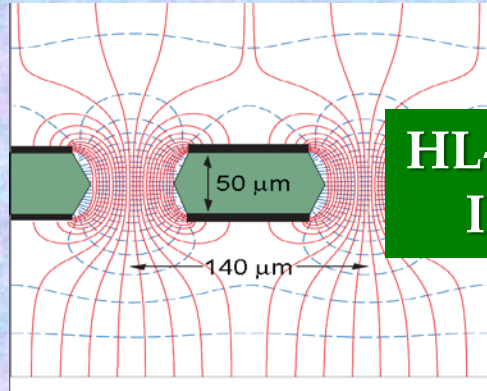
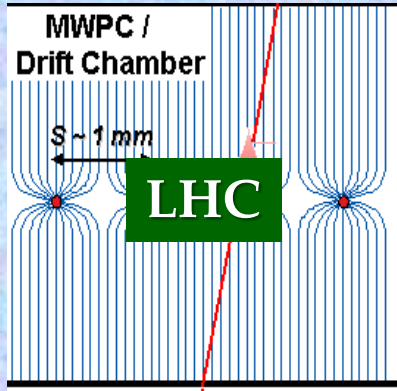
YESTERDAY:

INTEGRATION →

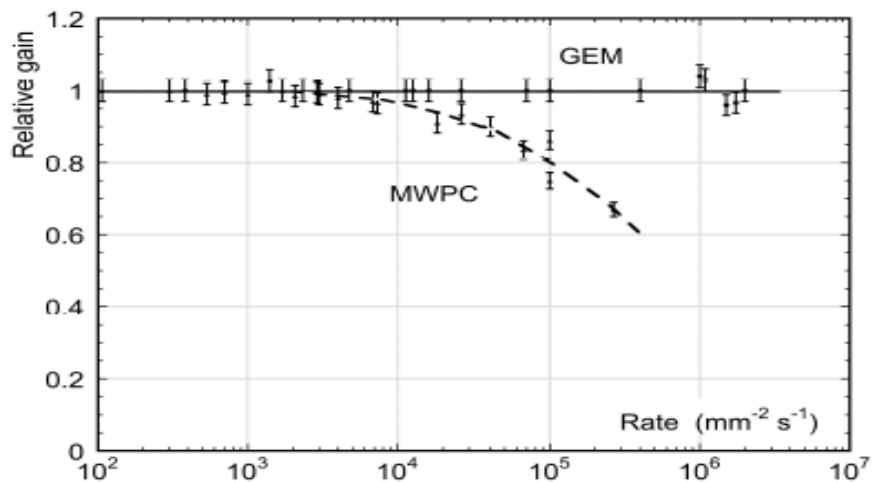
TODAY:

INTEGRATION →

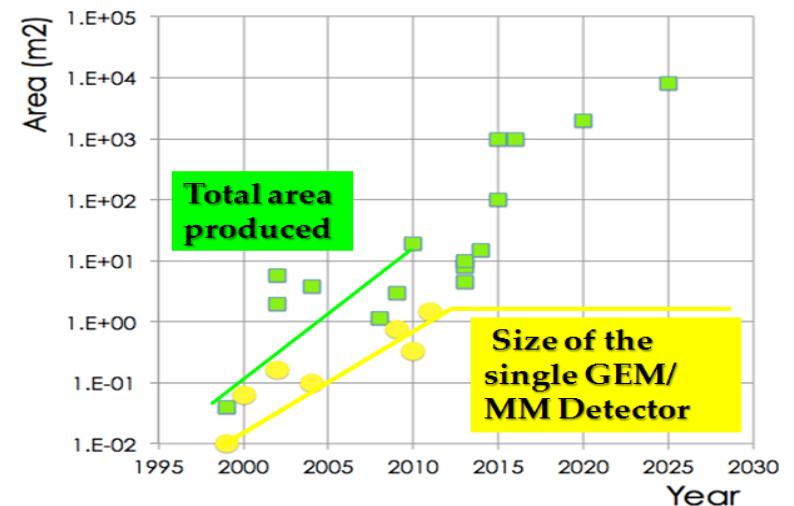
FUTURE:



- High rate capability  $\sim 10^6$  Hz/mm<sup>2</sup>
- Spatial res.  $\sim 30$ -50 μm (**TRACKING**)
- Time res.  $\sim 3$ -5 ns (**TRIGGER**)



Advances in photolithography → Large Area MPGDs ( $\sim$  m<sup>2</sup> unit size)





# Instead of Outlook ... MPGD Performance Summary

MPGD Characteristics	Gas Electron Multipliers (GEM)	Micromegas/ Resistive MM
➤ Active areas (Size of single detector module) / Large Scale Industrial Production	$\sim 1 \times 0.5 \text{ m}^2$ yes	$\sim 2 \times 1 \text{ m}^2$ yes
➤ Radiation Hardness	> 10 HL-LHC years	> 10 HL-LHC years
➤ High-Rate Capability	$\sim 50 \text{ MHz/cm}^2$	$\sim 50 \text{ MHz/cm}^2$
➤ Spatial resolution		$< \sim 30 \mu\text{m}$ (single layer) ang. dep.: $\mu\text{TPC}$
➤ Tracking efficiency	99%	98%
➤ Timing resolution	95-98%	95-98%
➤ Time resolution	$\sim 4\text{-}5 \text{ ns}$ (MIP) & $\text{CF}_4$ how to improve (?)	$3\text{-}5 \text{ ns}$ (MIP) & $\text{CF}_4$ how to improve (?)

MPGDs have also found numerous applications → they are being used or considered:  
 X-ray and neutron imaging, neutrino–nucleus scattering experiments, dark-matter  
 and astrophysics experiments, plasma diagnostics, material sciences, radioactive-waste  
 monitoring and security applications, medical physics and hadron therapy.