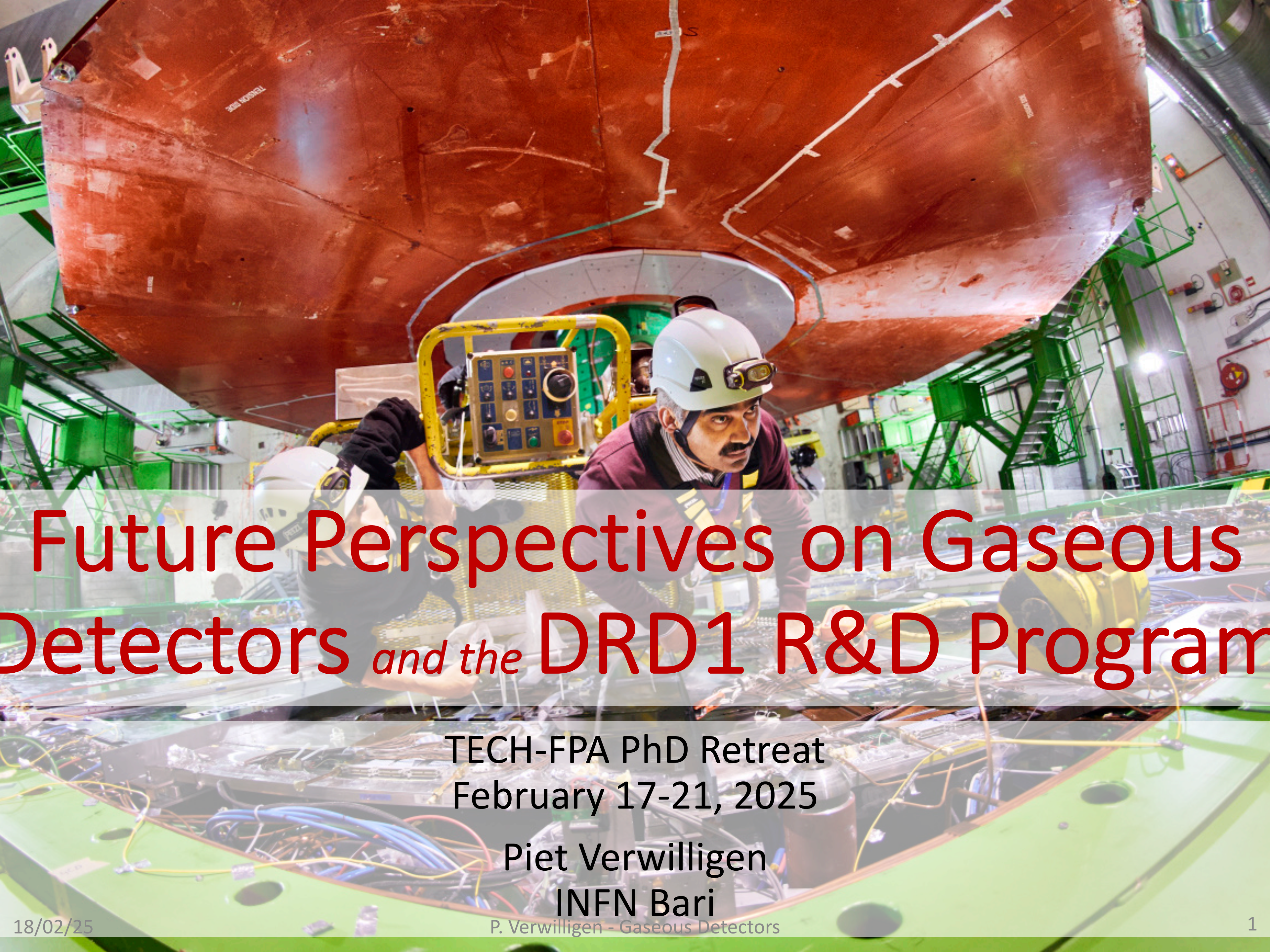


Future Perspectives on Gaseous Detectors *and the* DRD1 R&D Program

TECH-FPA PhD Retreat
February 17-21, 2025

Piet Verwilligen
INFN Bari

Future Perspectives on Gaseous Detectors

and DRD1 R&D Program

OUTLINE

1. Introduction
2. Operating principles
3. A historical Introduction
4. High-Luminosity LHC Upgrades
5. R&D on Gaseous Detectors
6. DRD1 Collaboration

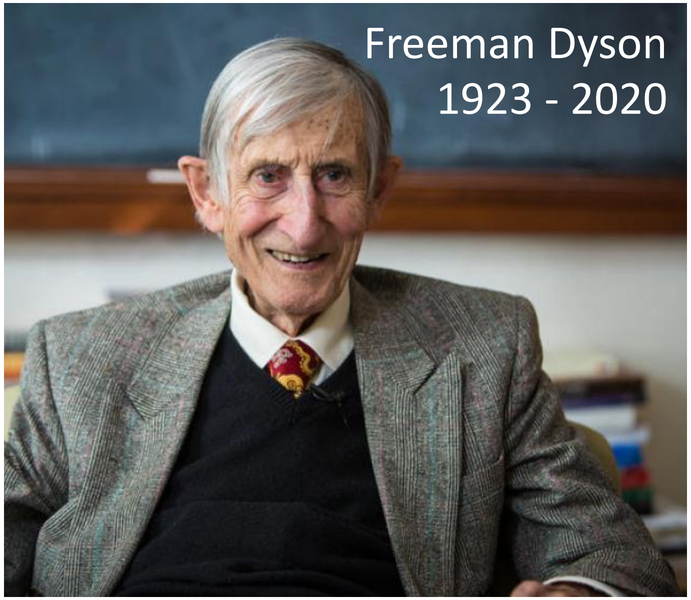
Future Perspectives on Gaseous Detectors

1. Introduction – On Tools and Instrumentation

“New directions in Science are launched by new tools much more often than by new concepts”

The effect of a concept-driven revolution is to explain old things in new ways”

The effect of a tool-driven revolution is to discover new things that have to be explained”



Freeman Dyson (Imagined Worlds)

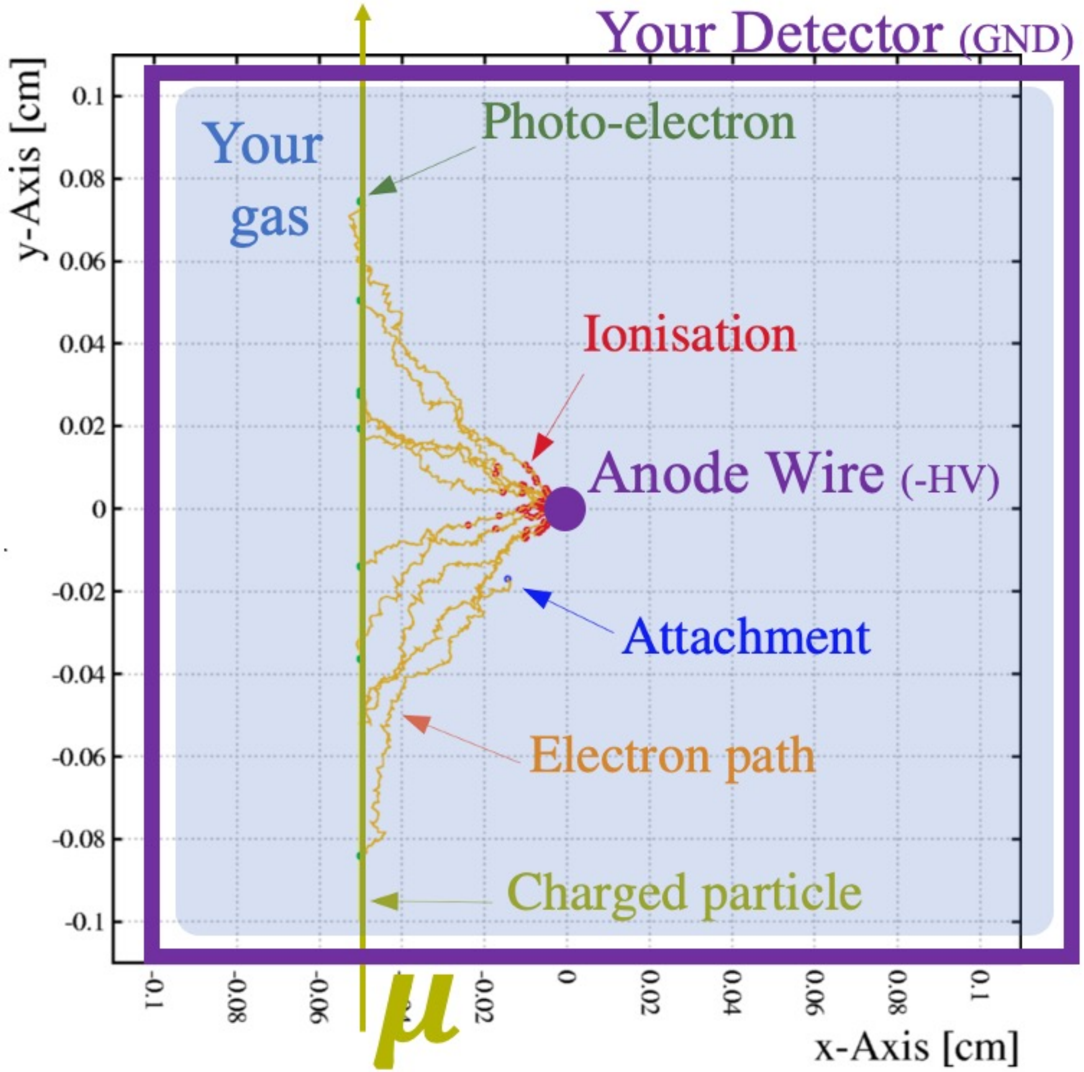
Nobel Prizes in Physics (statistics @ 2008 by W.Riegler)
- 31 for Theory
- 56 for Experiments & Instrumentation

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber

Idea & Slide © Werner Riegler

Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles



Primary Ionization
- *Energy loss - gas*
- *Cluster distribution*

Your Detector
- *Geometry*
- *Electric Fields*

Charge transport
- *Drift & diffusion*
- *Gas cross-sections*

Charge Amplification
- *Townsend avalanche*
- *Avalanche fluctuations*

Signal Induction
- *Ramo-Shockley theorem*
- *Signal processing*

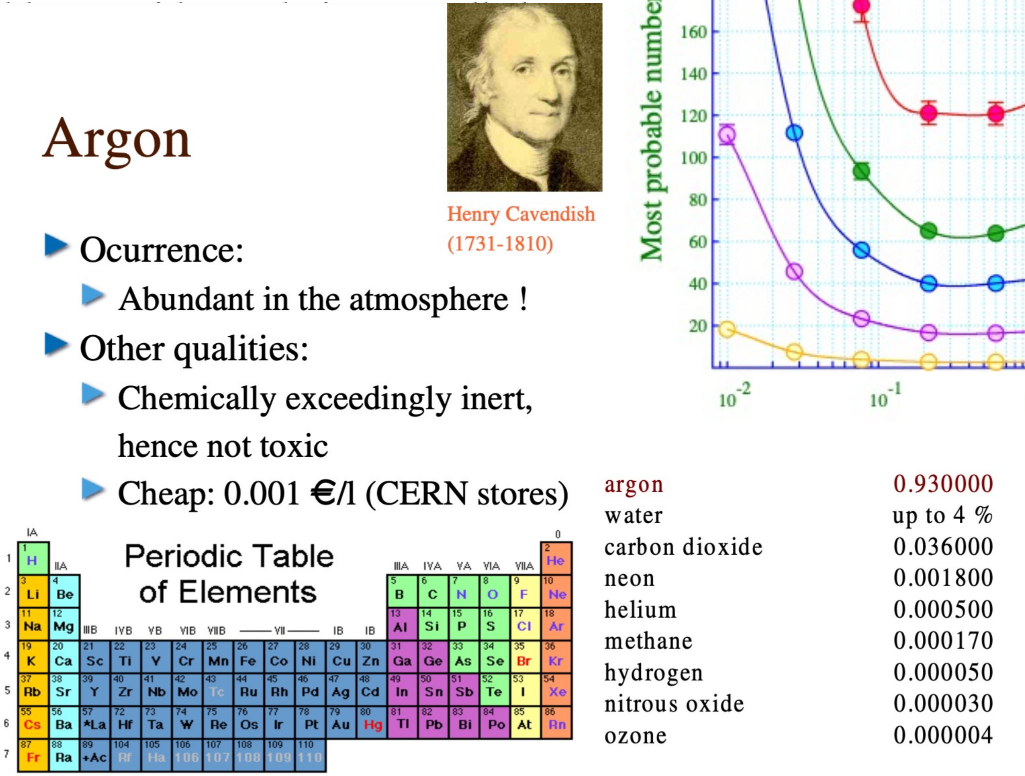
Plot © Rob Veenhof

Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Choice of Gas (mixture)

- Which gas would be suitable ?
  - easily ionisable;
  - not attaching: doesn't swallow electrons;
  - neither flammable, nor explosive, nor toxic;
  - no sparks in strong electric fields.

- Typically one uses a n
  quencher, of molecula

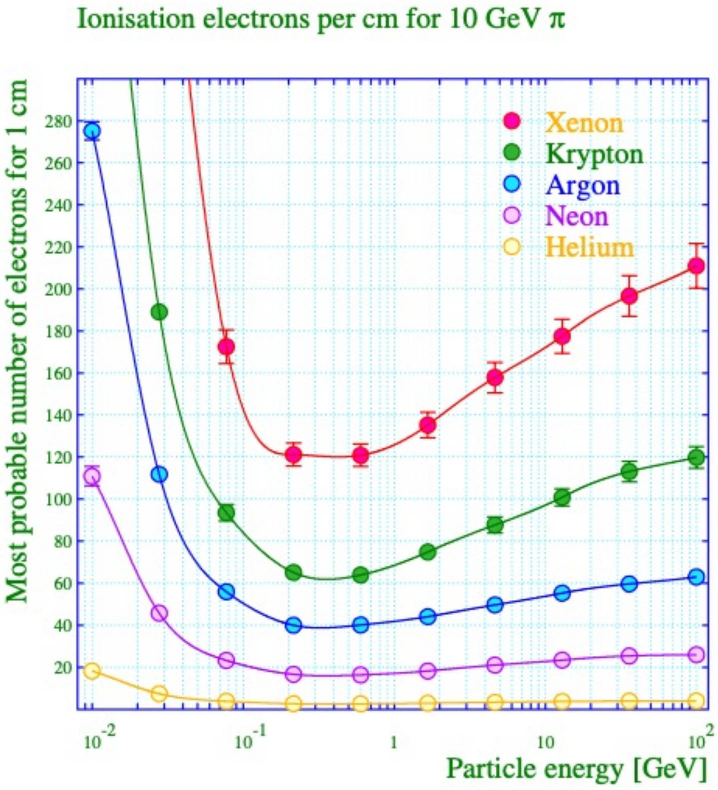


Argon

Henry Cavendish
(1731-1810)

- Ocurrence:
  - Abundant in the atmosphere !
- Other qualities:
  - Chemically exceedingly inert, hence not toxic
  - Cheap: 0.001 €/l (CERN stores)

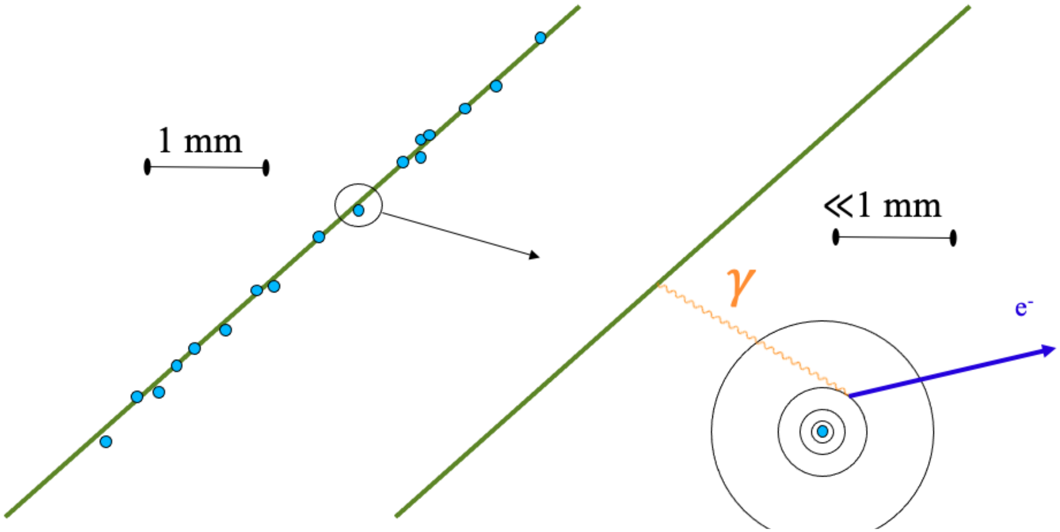
argon	0.930000
water	up to 4 %
carbon dioxide	0.036000
neon	0.001800
helium	0.000500
methane	0.000170
hydrogen	0.000050
nitrous oxide	0.000030
ozone	0.000004



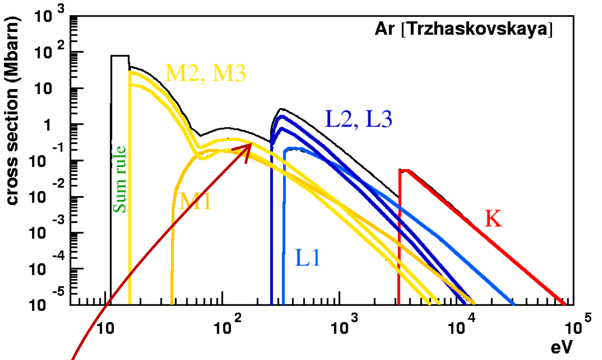
Slide © Rob Veenhof

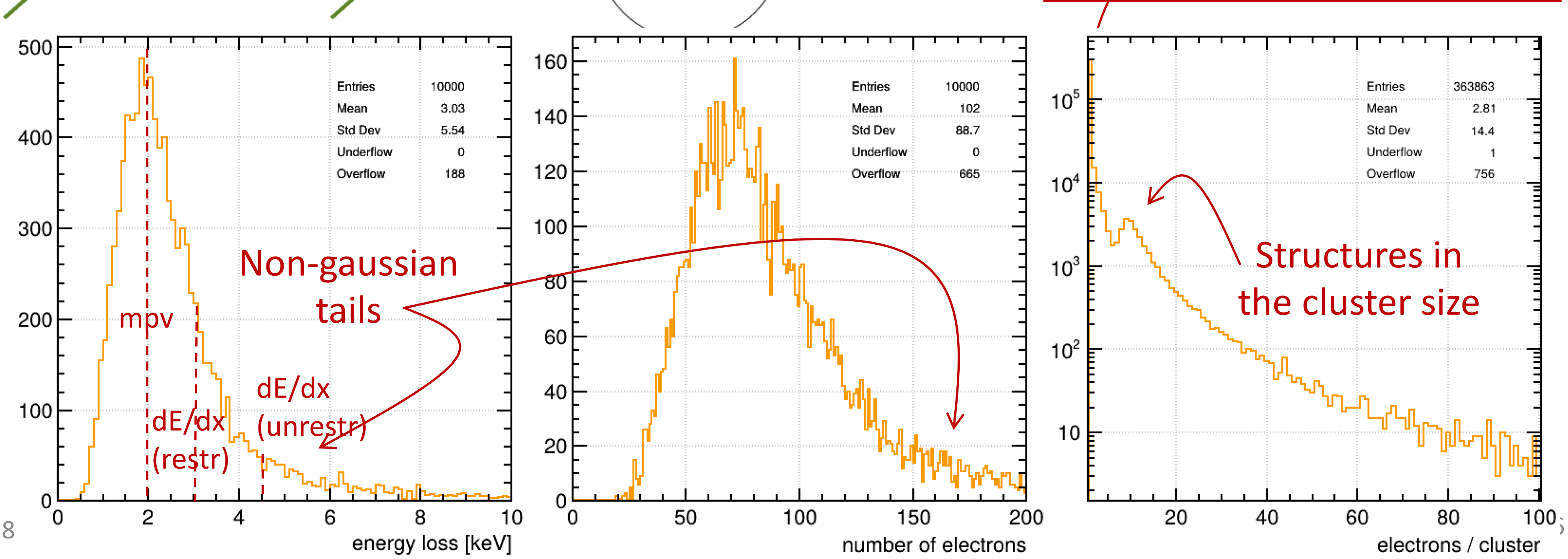
Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Primary Ionization



Remember, if energy of γ^* is high enough to ionize on the L-shell we have a jump in σ_γ





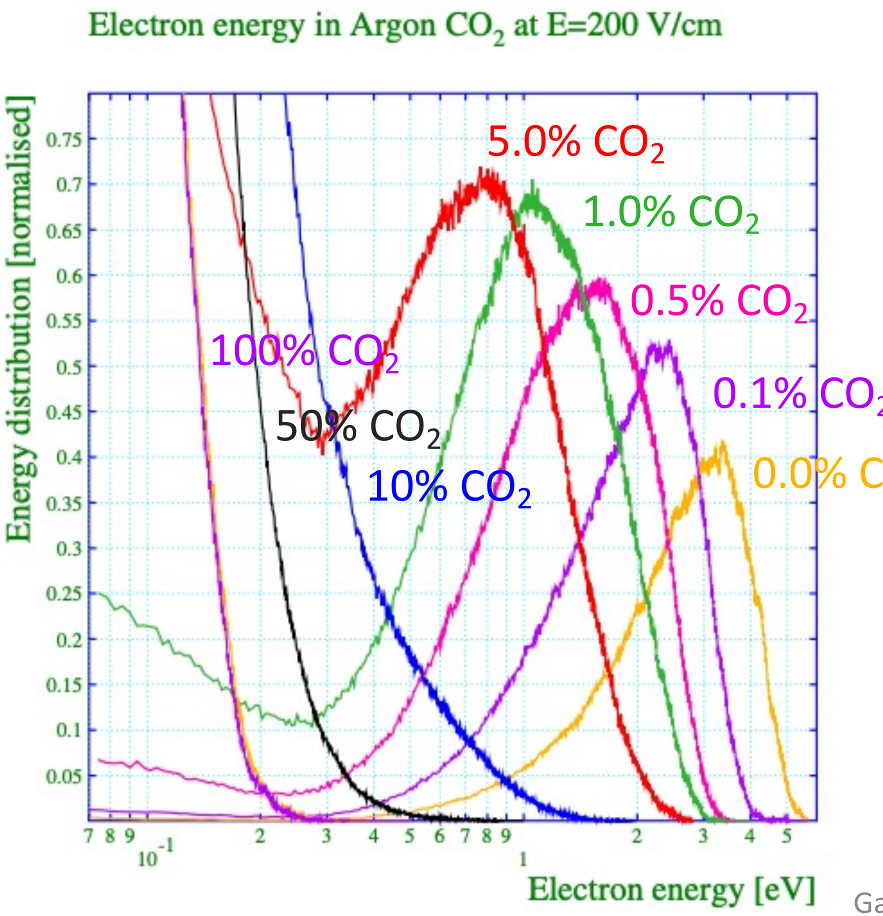
Non-gaussian tails

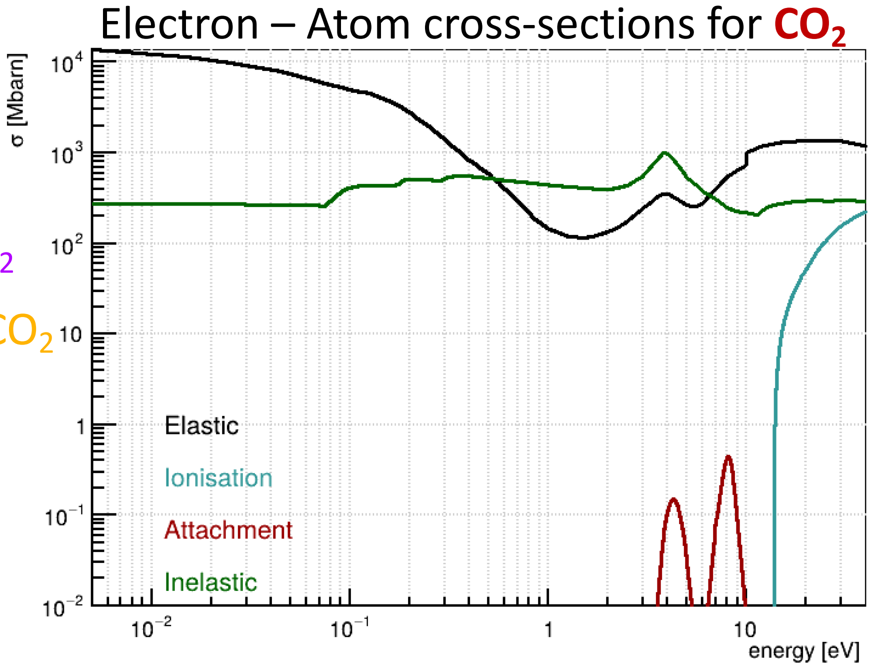
Structures in the cluster size

Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Charge Transport

- Drift velocity of electrons in pure Argon is slow – why?
- Add a quencher gas: e.g. CO_2

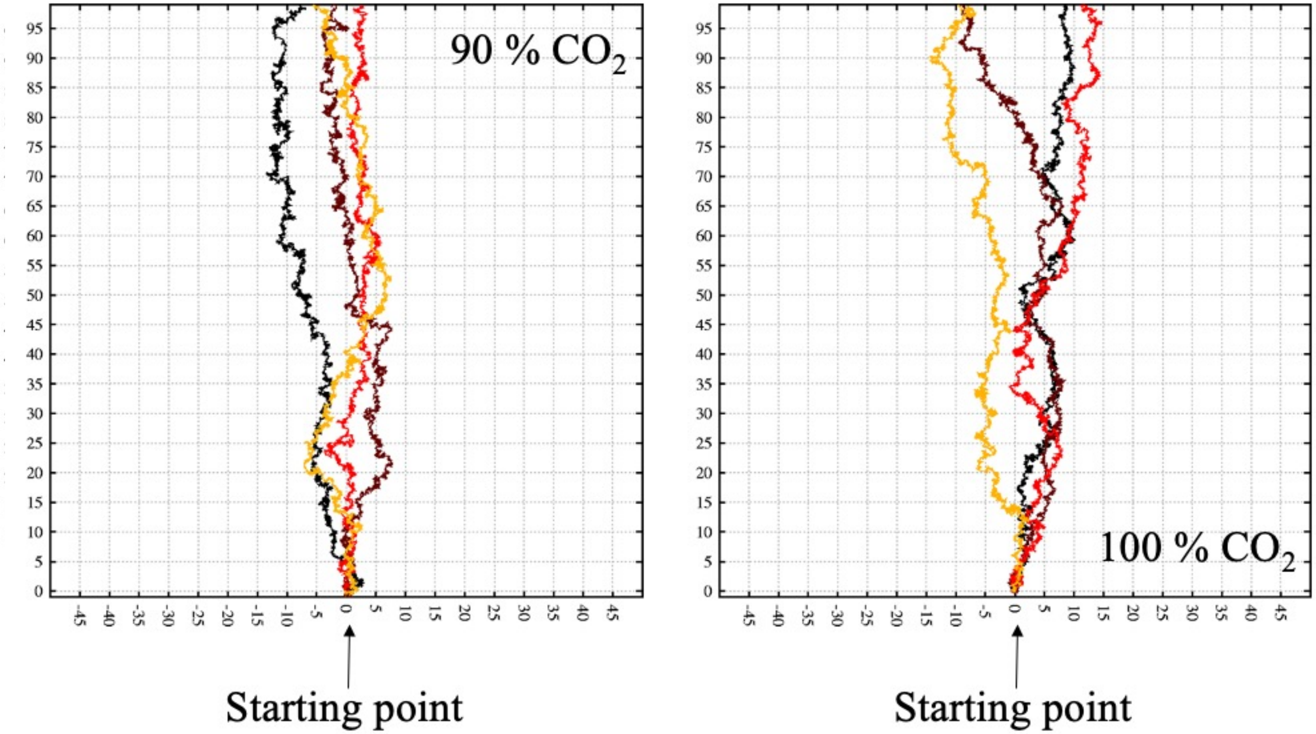




Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Charge Transport

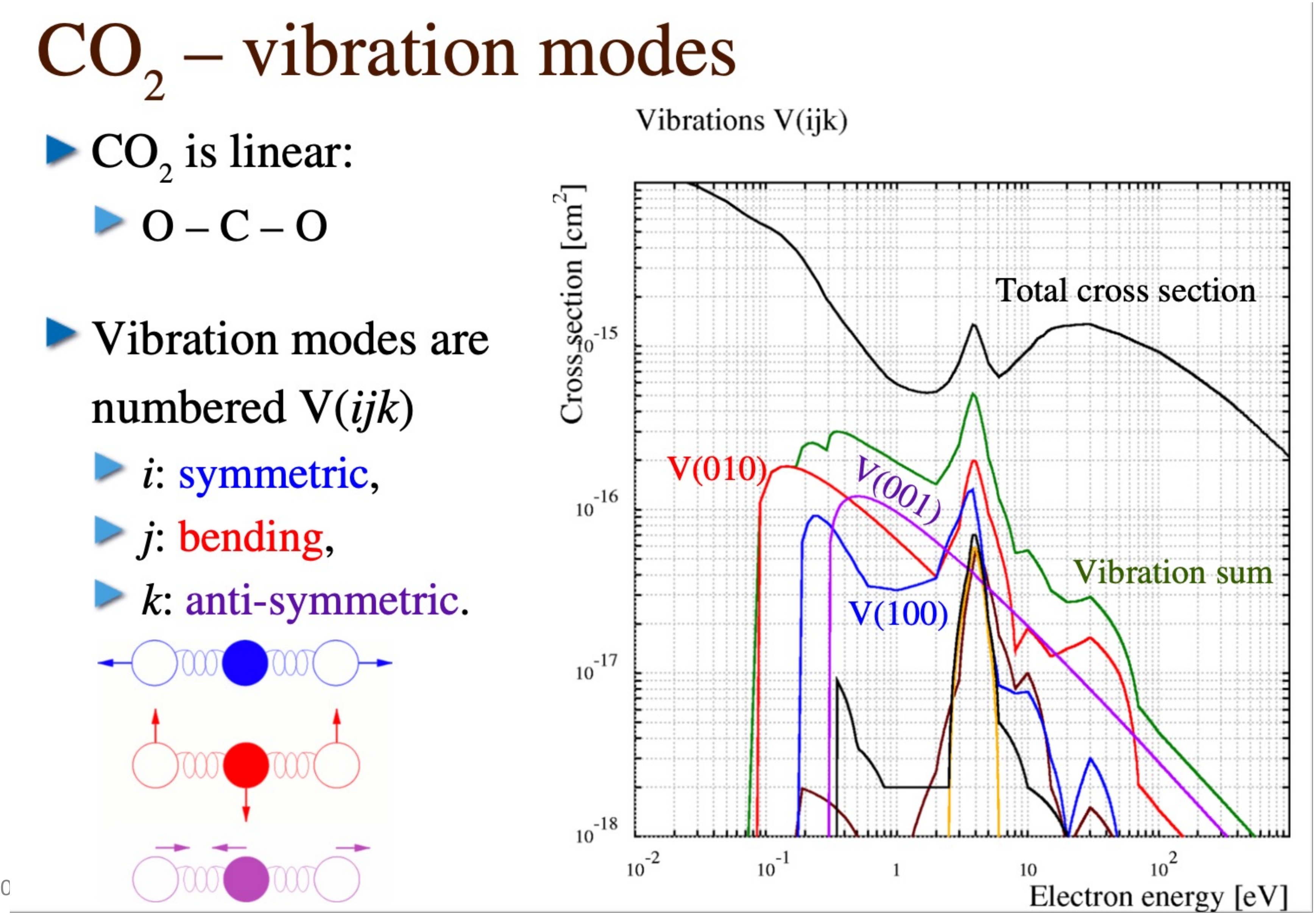
- Drift velocity of electrons in pure Argon is slow – why?
- Add a quencher gas: e.g. CO_2
- Microscopic Simulation of an electron in Ar:CO_2 @ 1kV/cm



Plots © Rob Veenhof

Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Charge Transport



CO_2 – vibration modes

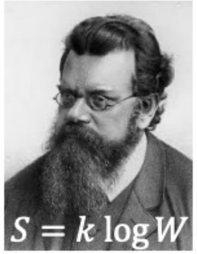
- CO_2 is linear:
  - O – C – O
- Vibration modes are numbered V(*ijk*)
  - *i*: symmetric,
  - *j*: bending,
  - *k*: anti-symmetric.

Vibrations V(ijk)

Slides © Rob Veenhof

Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Charge Transport



Boltzmann equation

- The Boltzmann equation describes the evolution of the distribution function f (energy or velocity distribution) in 6D phase-space: $f(\boldsymbol{x}, \boldsymbol{v})$ is function of position and velocity

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla f + \frac{e}{m}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \nabla f = 0$$

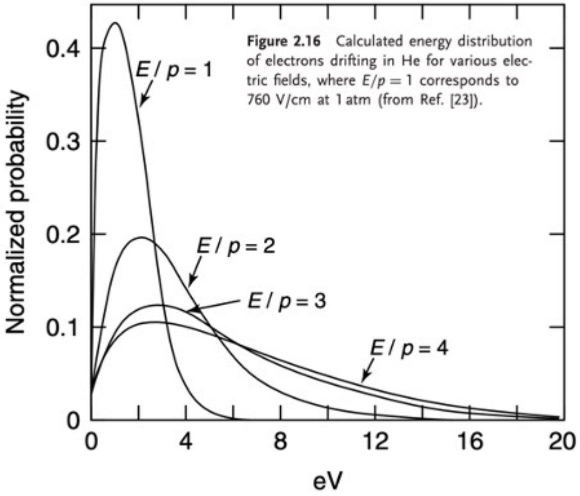
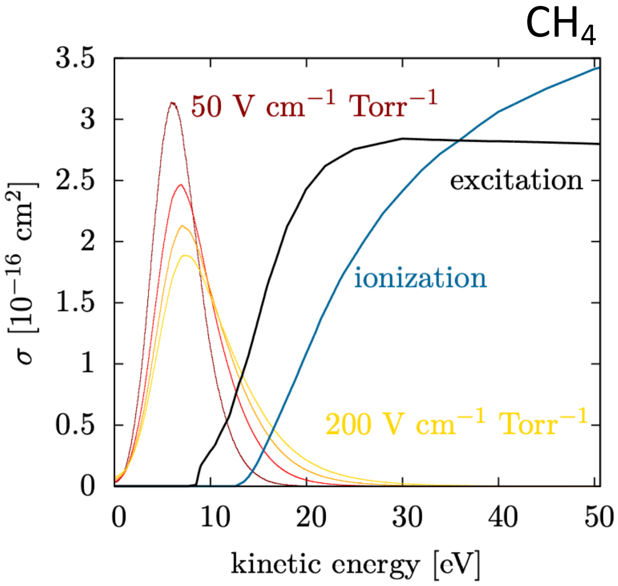


Figure 2.16 Calculated energy distribution of electrons drifting in He for various electric fields, where $E/p = 1$ corresponds to 760 V/cm at 1 atm (from Ref. [23]).

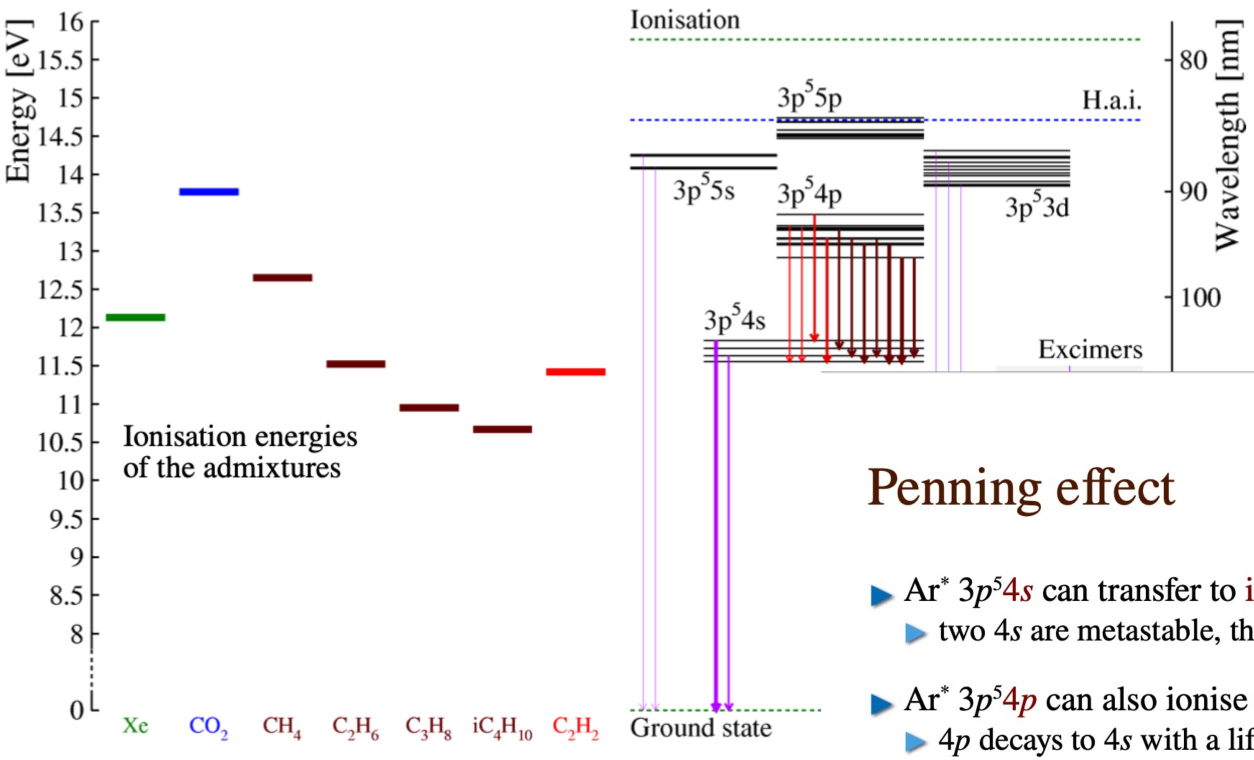


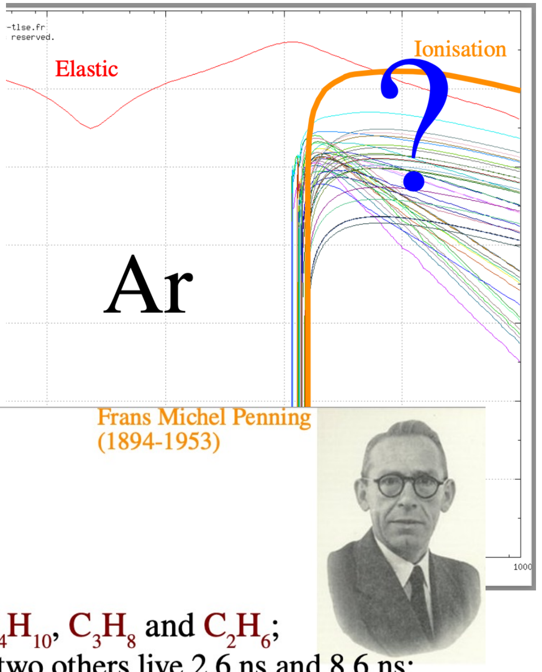
Plot © H Schindler

Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Charge Amplification

Level diagram argon and admixtures





Frans Michel Penning (1894-1953)

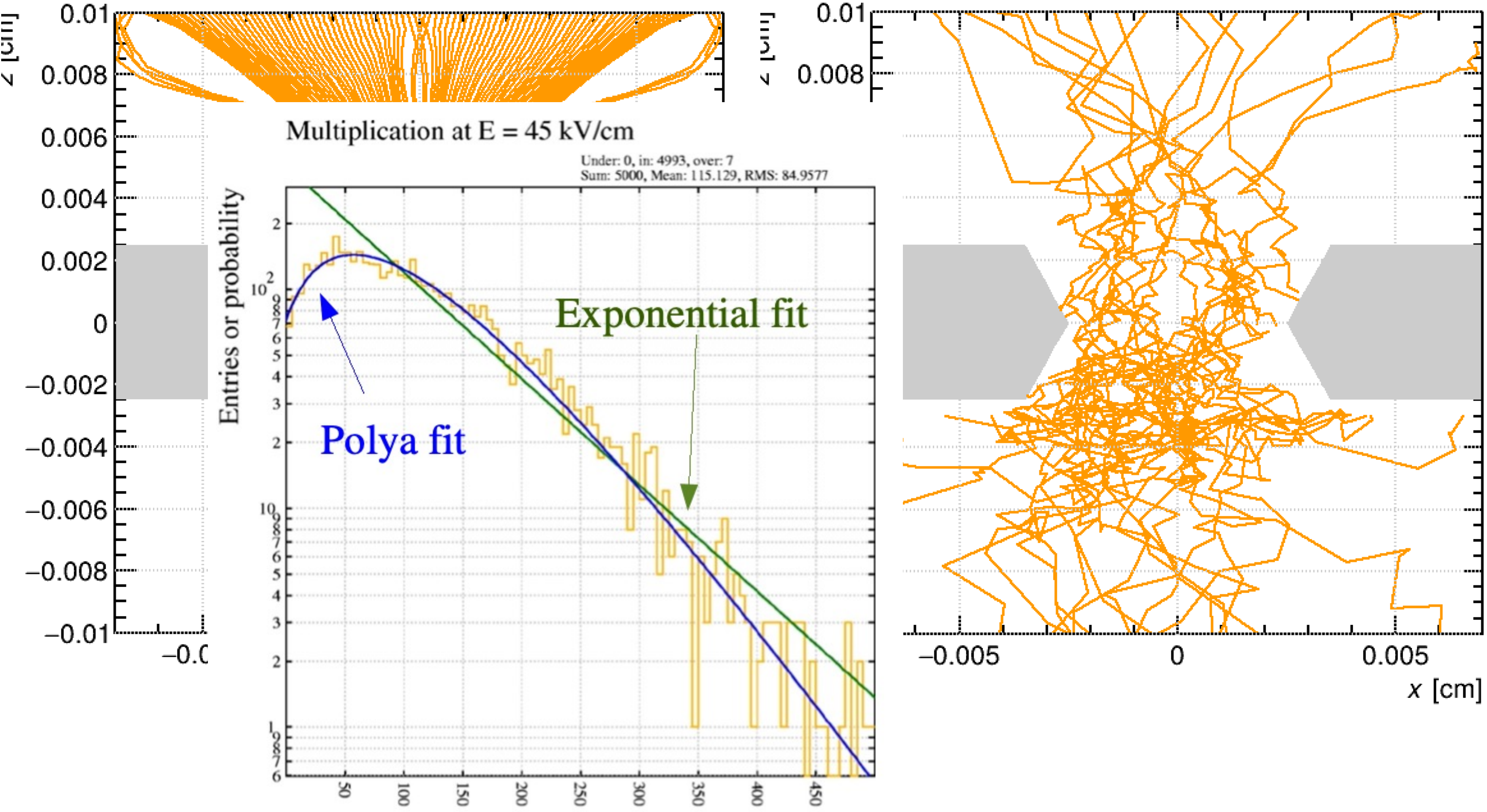
Penning effect

- Ar* $3p^5$4*s* can transfer to iC_4H_{10}, C_3H_8 and C_2H_6;
  - two 4*s* are metastable, the two others live 2.6 ns and 8.6 ns;
- Ar* $3p^5$4*p* can also ionise CH_4;
  - 4*p* decays to 4*s* with a lifetime of 20-40 ns;
- Ar* $3p^5$3*d* can in addtion transfer to CO_2;
  - radiative 3*d* decays take ~3.5 ns, the others ~50 ns.

Slides © Rob Veenhof

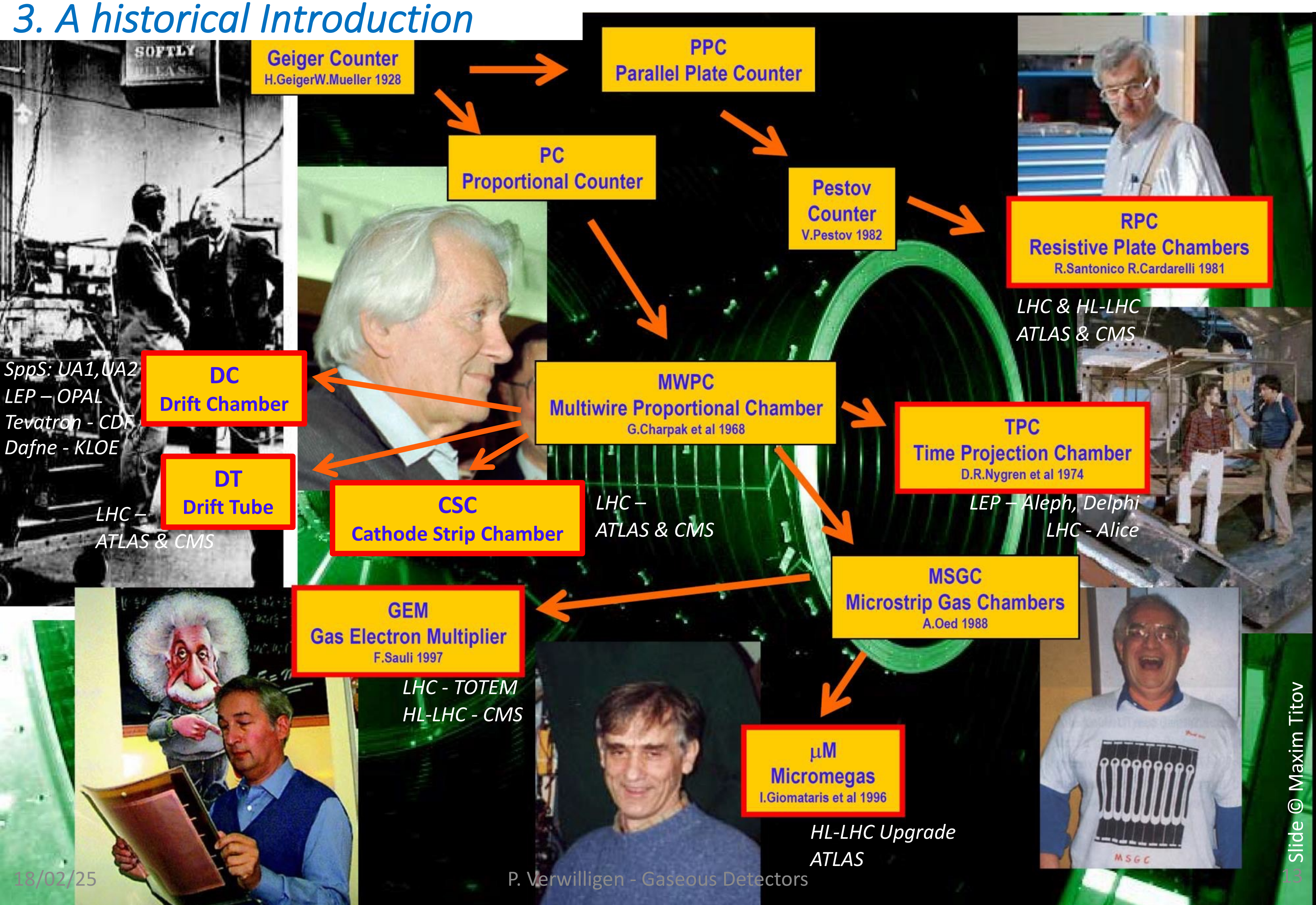
Future Perspectives on Gaseous Detectors

2. Gaseous Detectors Operating Principles: Charge Amplification



Gaseous Detectors – a very brief history

3. A historical Introduction



Geiger Counter
H.GeigerW.Mueller 1928

PPC
Parallel Plate Counter

PC
Proportional Counter

Pestov Counter
V.Pestov 1982

RPC
Resistive Plate Chambers
R.Santonico R.Cardarelli 1981

LHC & HL-LHC
ATLAS & CMS

MWPC
Multiwire Proportional Chamber
G.Charpak et al 1968

DC
Drift Chamber

SppS: UA1,UA2
LEP – OPAL
Tevatron - CDF
Dafne - KLOE

DT
Drift Tube

LHC –
ATLAS & CMS

CSC
Cathode Strip Chamber

LHC –
ATLAS & CMS

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

LEP – Aleph, Delphi
LHC - Alice

MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997

LHC - TOTEM
HL-LHC - CMS

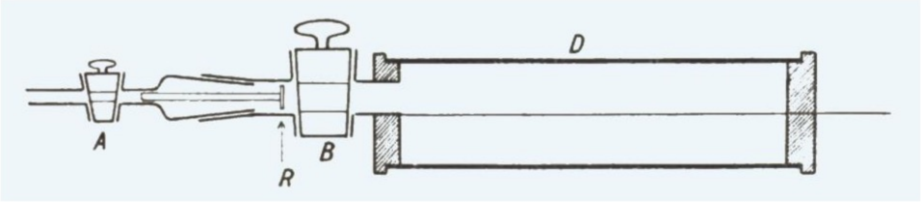
μM
Micromegas
I.Giomataris et al 1996

HL-LHC Upgrade
ATLAS

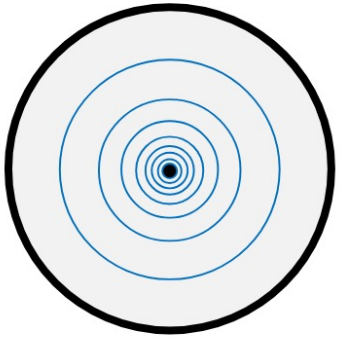
Slide © Maxim Titov

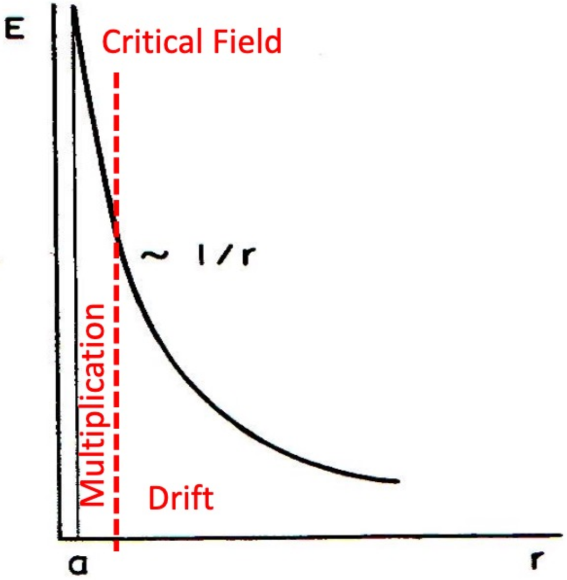
1st electronic particle Detector: SWPC (1908)

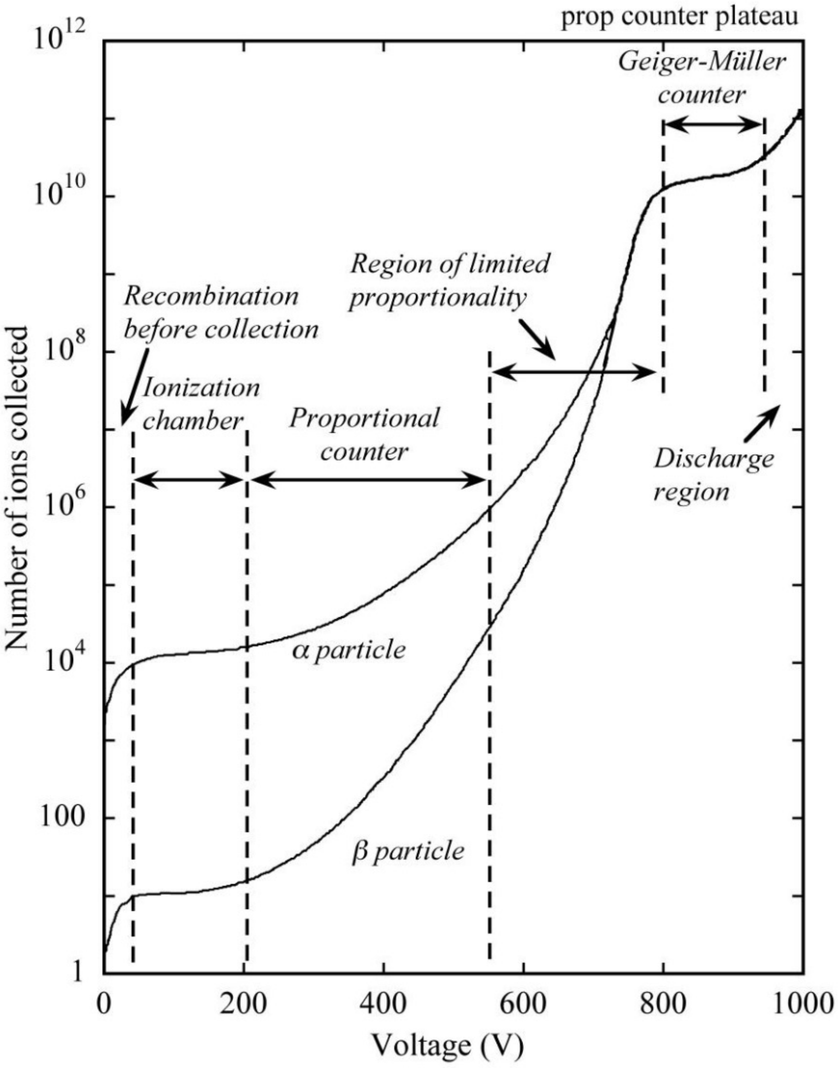
Single Wire Proportional Counter (SWPC)
Rutherford and Geiger (1908)



Radial Electric Field







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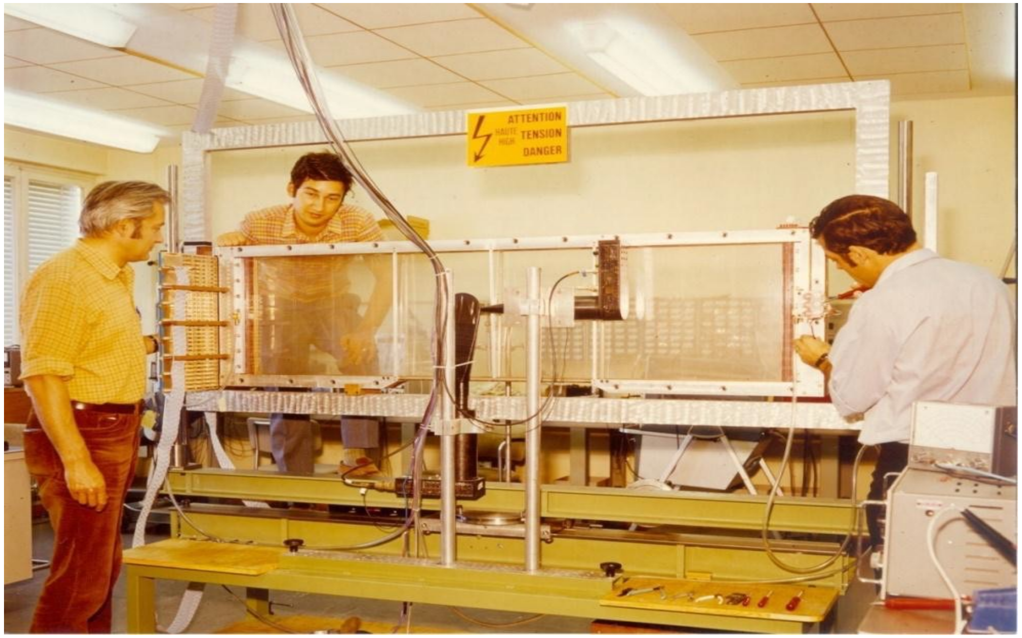
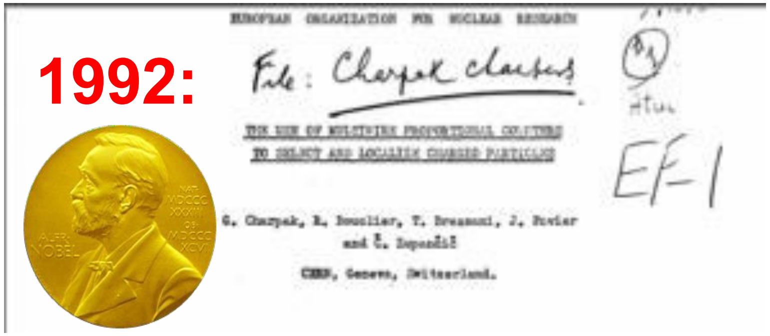
The Revolution of 1968: MWPC



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

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

1992:



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File: Charpak chambers

EF-I

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

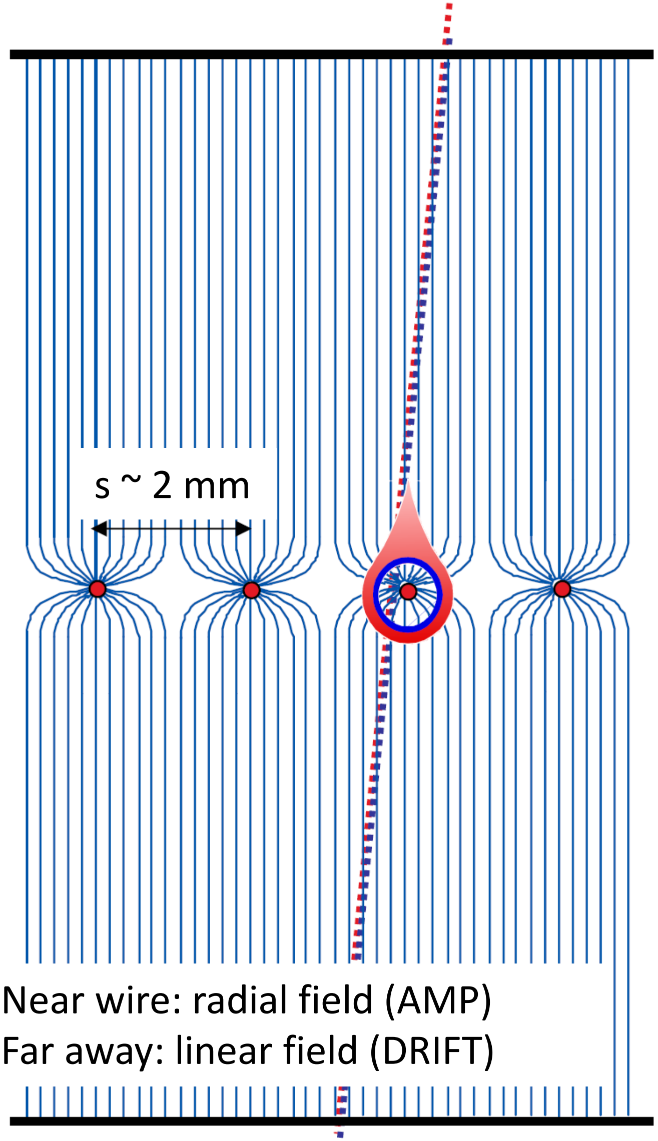
G. Charpak, R. Bouclier, T. Bressani, J. Favier
and Č. Zupančič

CERN, Geneva, Switzerland.

Slide © Maxim Titov

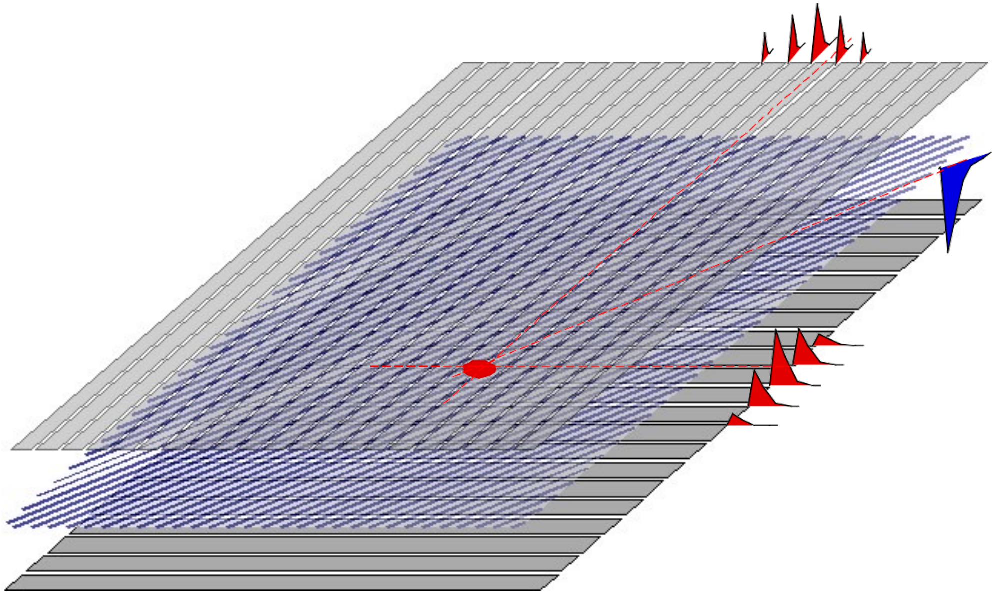
Multi-Wire Proportional Chamber (MWPC)

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



Near wire: radial field (AMP)
Far away: linear field (DRIFT)

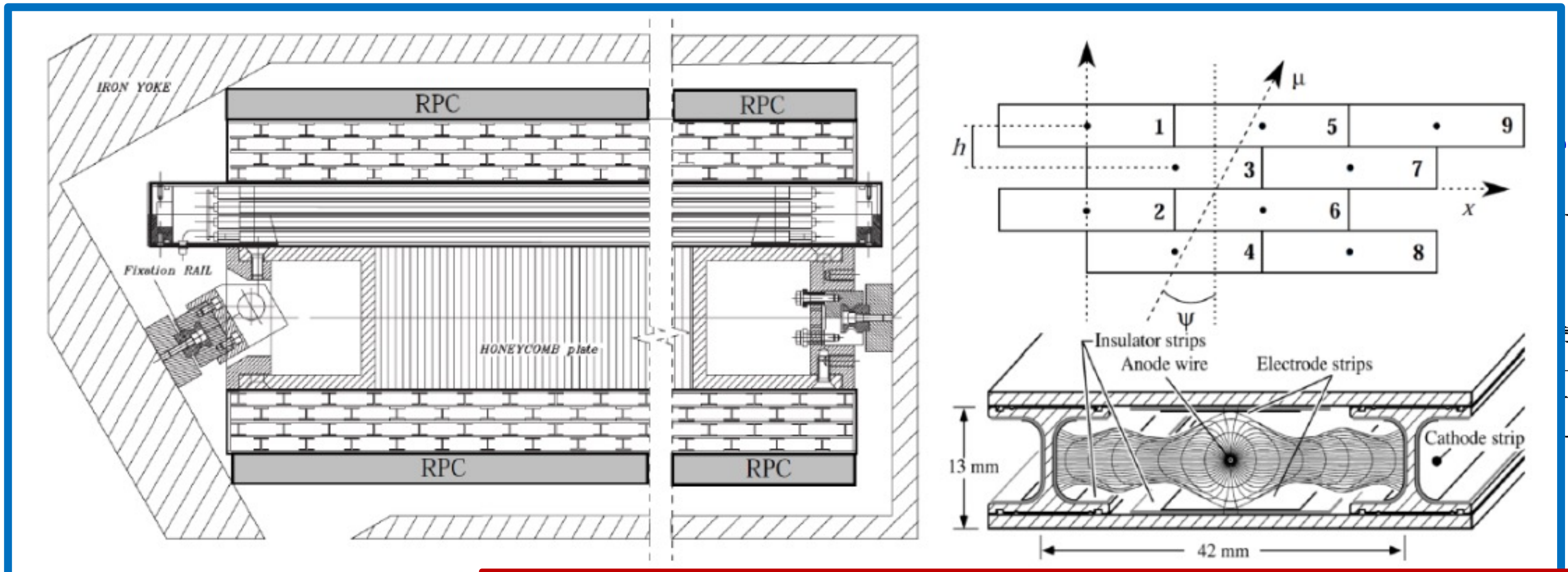
1. **High-rate MWPC with digital readout:**
   Spatial resolution limited by wire spacing: $\sigma_x = s/\sqrt{12}$ = 0.5 mm
2. **Charge readout from segmented cathode:**
   Spatial resolution determined by Signal/Noise (S/N)
   Typical (i.e. very good): S=20k, N=1k electrons: S/N=20, σ_x= 0.1 mm



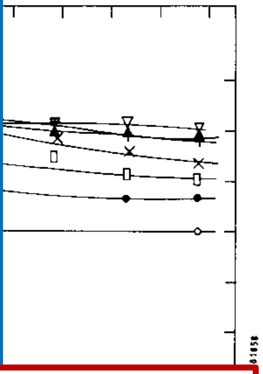
Spatial resolution limited by wire-spacing. Better resolution requires more wires closer together, which leads to instabilities. Segmented Cathode Readout => **Cathode Strip Chambers (CSC)**

Slide © Maxim Titov

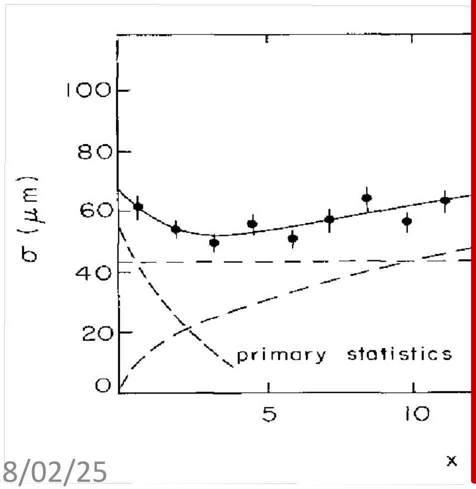
Drift Chamber (DC) & Drift Tube (DT)



- time relation r(t)



Addition of Field-shaping wire to avoid low field region



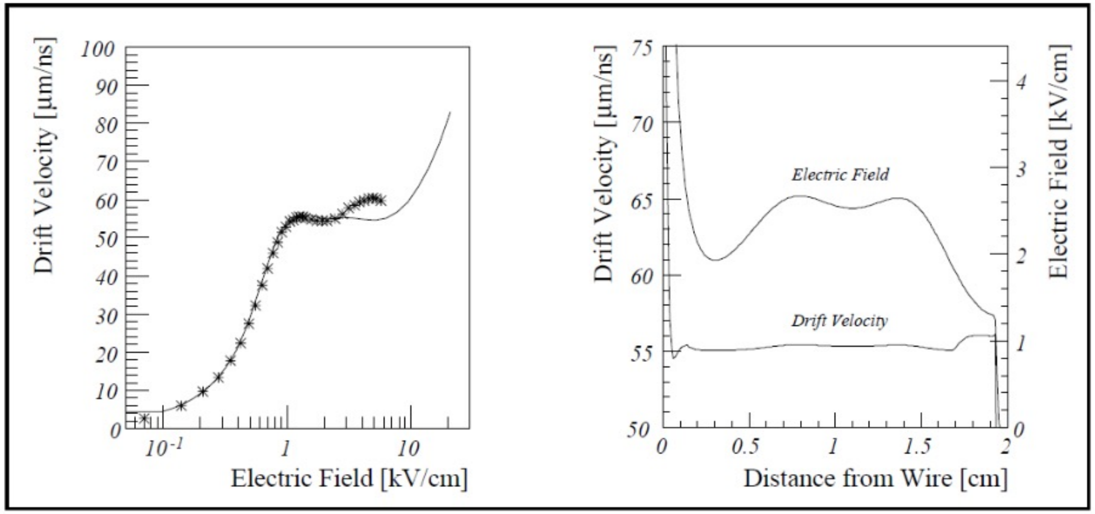


Fig. 3.2.5: a) (left) drift velocity vs. electric field for simulations and measurement with the final gas choice (Ar/CO$_2$ 85/15); b) (right) drift velocity across the drift cell; it can be seen that a good linearity is present in the entire cell.

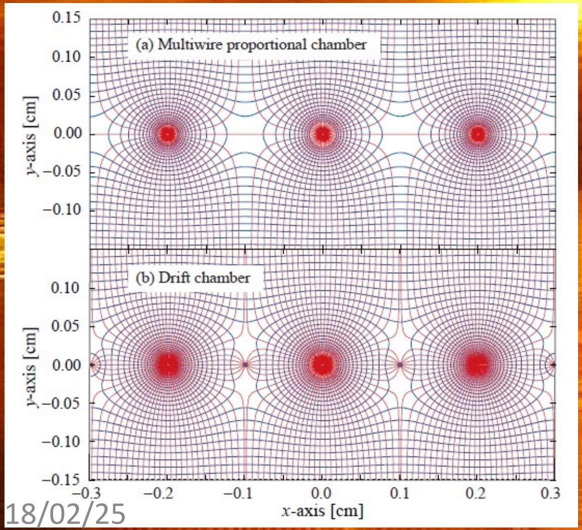
Slide © Maxim Titov

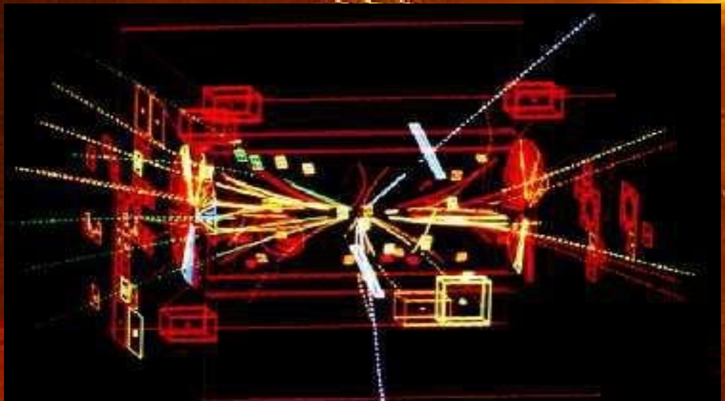
Drift Chamber: Discovery of W & Z bosons

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

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

1984:





Z ➔ *ee* (white tracks) at UA1/CERN

Slide © Maxim Titov

Birth of the Time Projection Chamber (TPC)

TPC

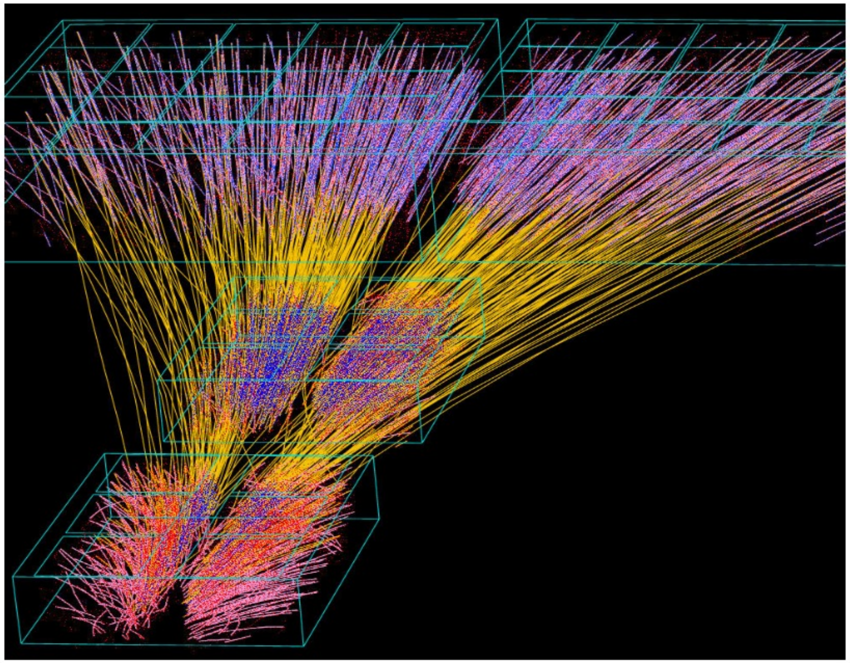
- Typically very large
- Almost empty inside
- Excellent for dealing with large numbers of tracks

- 1976: David Nygren (for PEP4)

David Nygren

Alice

Star



NA49

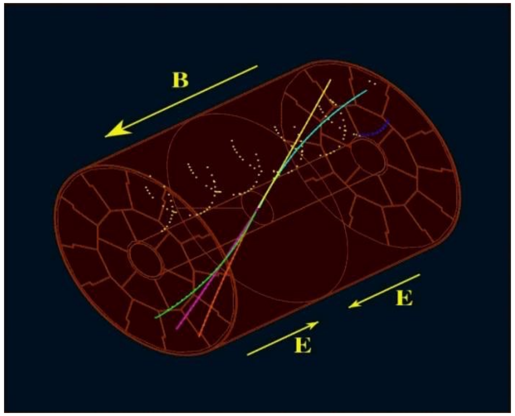
Slide © Rob Veenhof

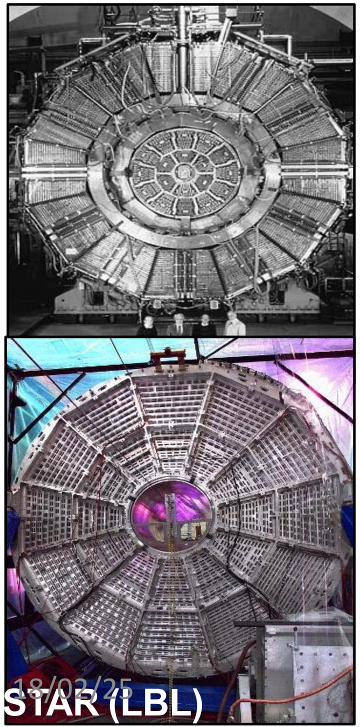
Birth of the Time Projection Chamber (TPC)

PEP4 (SLAC)

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

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





STAR (LBL)

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

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

ALICE TPC (CERN)

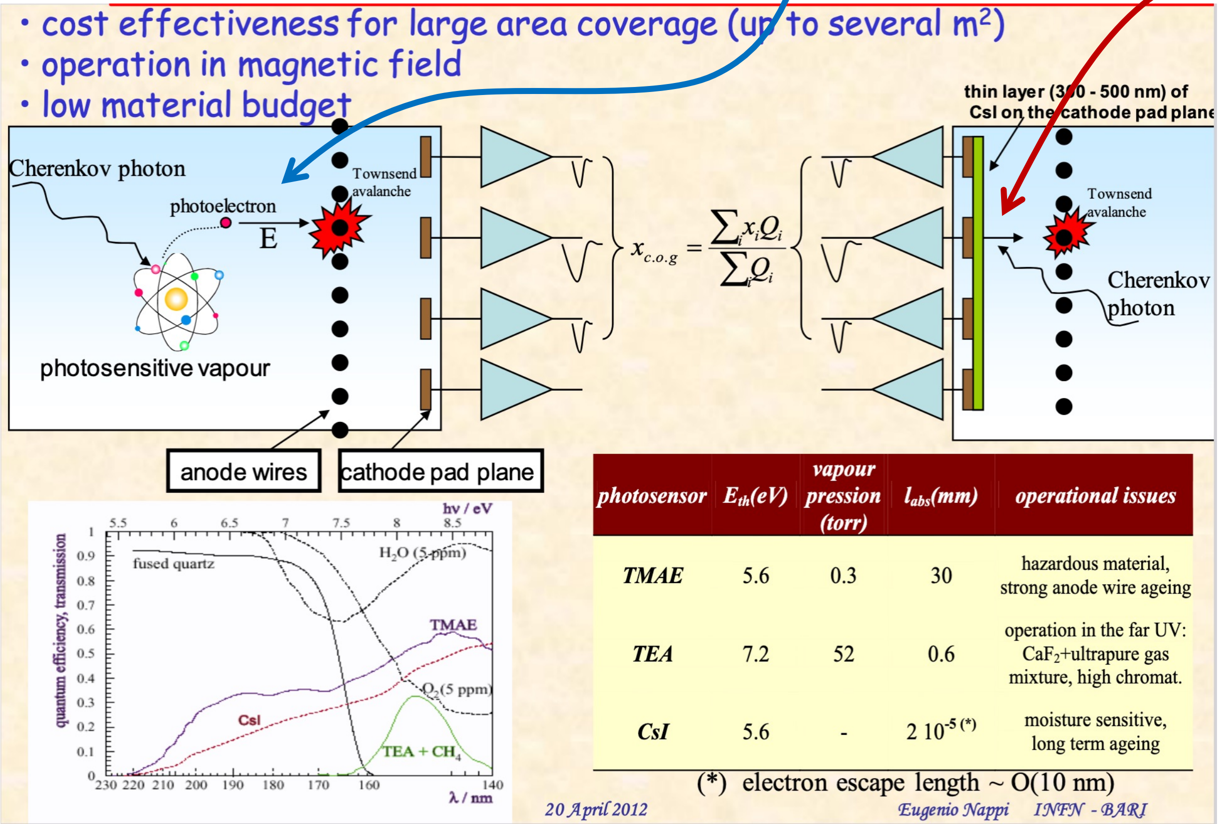
2021: Replace MWPC-readout with 4-GEM staggered holes

Slide © Maxim Titov

MWPC as UV-Photon detector in RICH

NEW Slide

- Ring Imaging Cherenkov (RICH) detectors
  - Idea: identify a charged particle (measure velocity) by measuring the opening angle of the (UV) Cherenkov radiation generated by the particle in a Cherenkov radiator
  - Only few UV photons detected, need good spatial resolution to reconstruct the ring => Gaseous detectors with good position resolution, e.g. MWPC
  - 2 Approaches: **photo-sensitive gases: TMAE, TEA** OR **solid-state γ-convertor (CsI)**



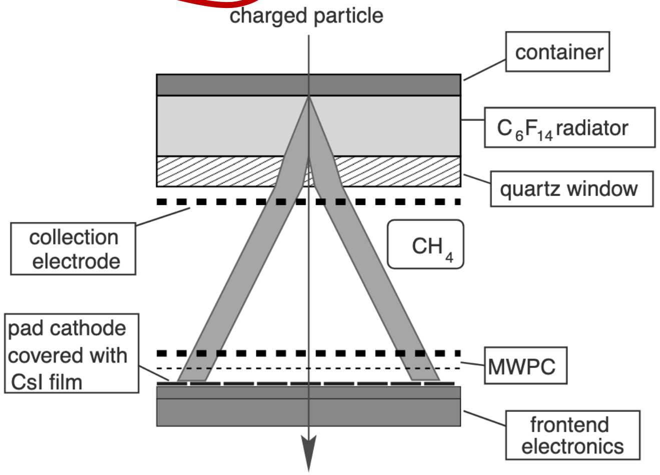
- cost effectiveness for large area coverage (up to several m²)
- operation in magnetic field
- low material budget

$$x_{c.o.g} = \frac{\sum_i x_i Q_i}{\sum_i Q_i}$$

photosensor	*E_{th}(eV)*	*vapour pression (torr)*	*l_{abs}(mm)*	*operational issues*
TMAE	5.6	0.3	30	hazardous material, strong anode wire ageing
TEA	7.2	52	0.6	operation in the far UV: CaF_2+ultrapure gas mixture, high chromat.
CsI	5.6	-	$2\ 10^{-5}$ (*)	moisture sensitive, long term ageing

(*) electron escape length ~ O(10 nm)

20 April 2012 *Eugenio Nappi INFN - BARI*



ALICE & COMPASS RICH:

- Readout pads covered with CsI
- Cherenkov-γ generated in C_6F14 (liquid radiator), passes through UV-transparent window (quartz)
- γ interacts in reflective photo-cathode (CsI)
- Ejected electron ionizes the gas and is detected by the MWPC

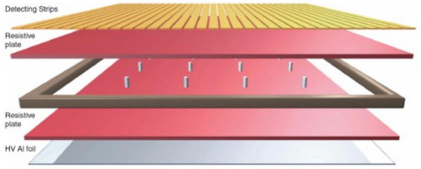
Slide © E. Nappi

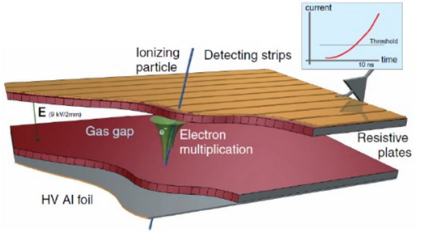
Gaseous Detectors with Parallel Plates

Resistive Plate Chambers (RPCs) & Multi-gap RPCs (MRPC)

- Parallel Plate chamber (PPCs) consist of thin (few mm) gas gap operated in an intense electric field, with excellent time resolutions (down to 50ps)
- PPCs improved by introduction of Resistive plates to quench the discharge (protect electronics) and keep rest of the detector active

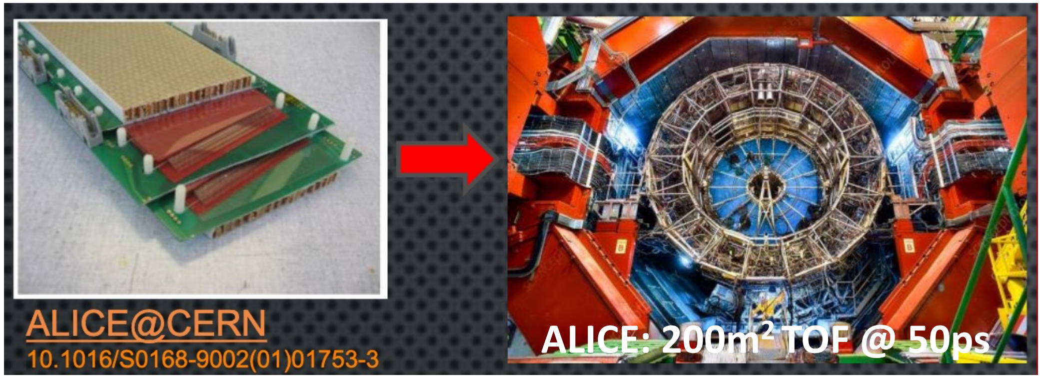
RPC





- Relatively new detector (1981–1988) developed by Santonico, Cardarelli (INFN Roma)
- Low cost alternative to fast large area scintillator detectors (expensive PM-tubes)
- Good time resolution, high efficiency, moderate spatial resolution

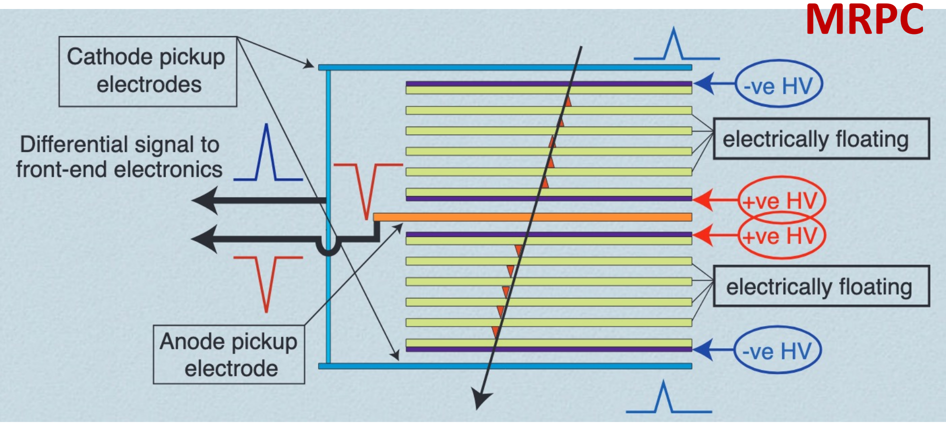
- 2 parallel plates with high resistivity
- small gas gap (∼ atm. pressure)
- high electric field (∼ 50 kV/cm)
- immediate multiplication of ionization e^-
- signal picked up by strips through capacitive coupling



ALICE@CERN
10.1016/S0168-9002(01)01753-3

ALICE: 200m² TOF @ 50ps

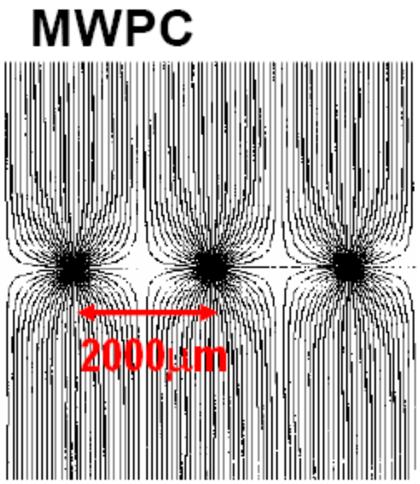
MRPC

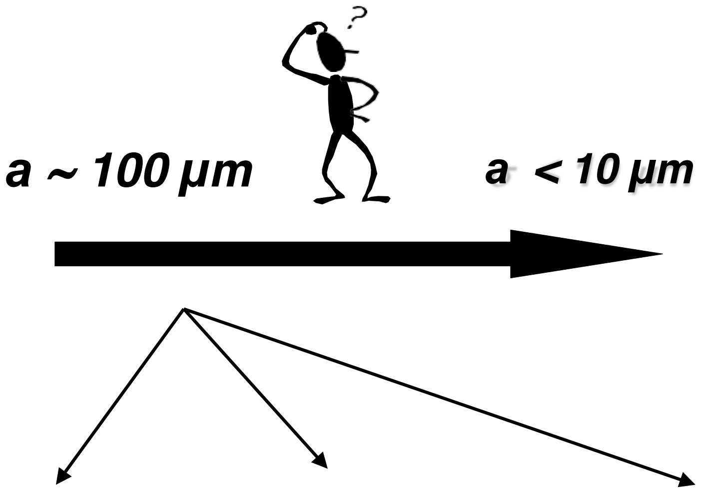


	RPC	MRPC
# gaps	1-2	10-20
Detect Size	$2 m^2$	$0.1 m^2$
System Size	5000-7500 m^2	$200 m^2$
Rate Cap	$\lesssim$ 10 kHz/cm²	$\lesssim$ 500 Hz/cm²
Time Res LHC	1-2ns	50-75ps
Time Res Prot	500 ps	15-20 ps

Micro-Pattern Gaseous Detectors:

Bridging gap between Wire Chambers and Silicon detectors



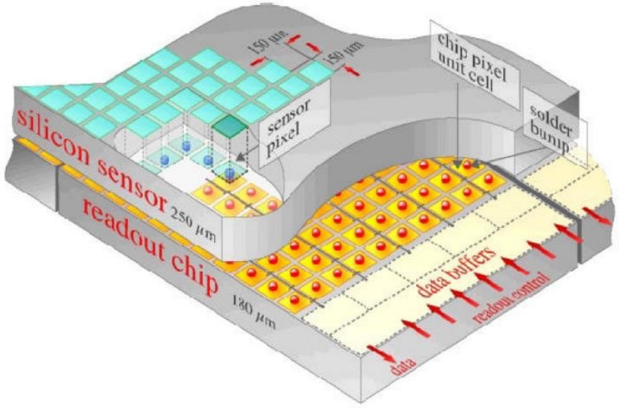


a ~ 100 µm

a < 10 µm

Pixel System:

Pixel System:



Advantages of gas detectors:

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

Problem:

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

Solution:

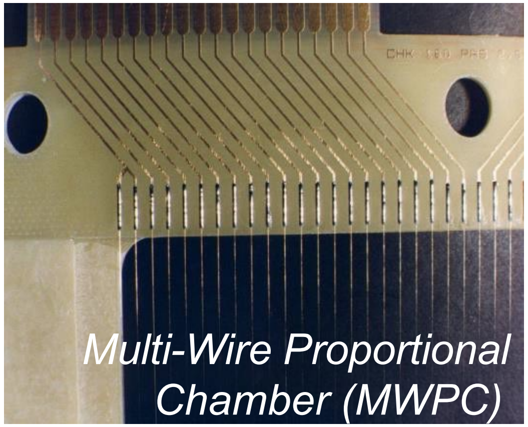
- ✓ ***reduction of the size of the detecting cell (limitation of the length of the ion path) using chemical etching and photo-lithographique techniques developed for microelectronics and keeping at same time similar field shape.***

Slide © Maxim Titov

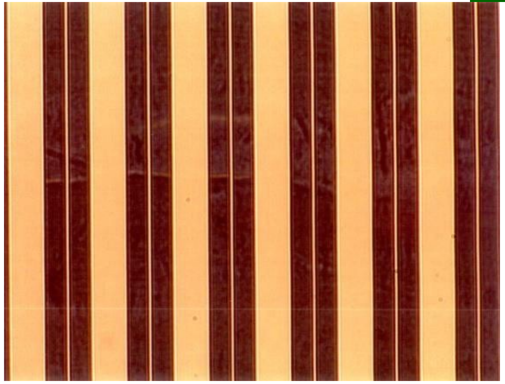
Micro-Strip Gas Chamber (MSGC)
An Early MPGD

Micro-Strip Gas Chamber (MSGC)

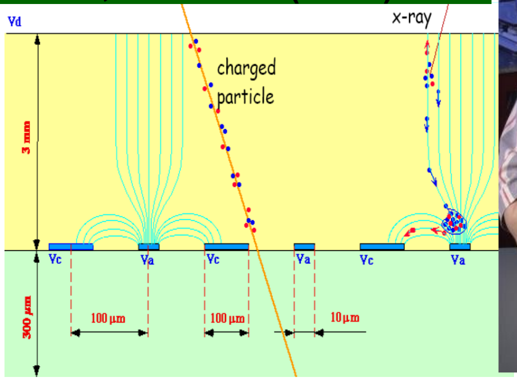
A. Oed, NIMA263 (1988) 351

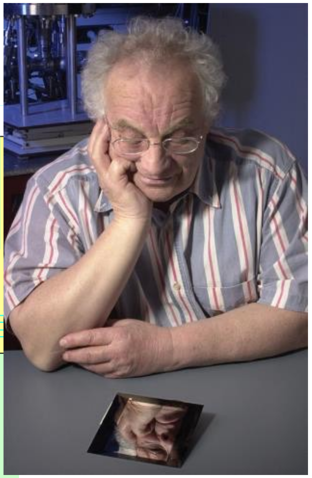


Multi-Wire Proportional Chamber (MWPC)



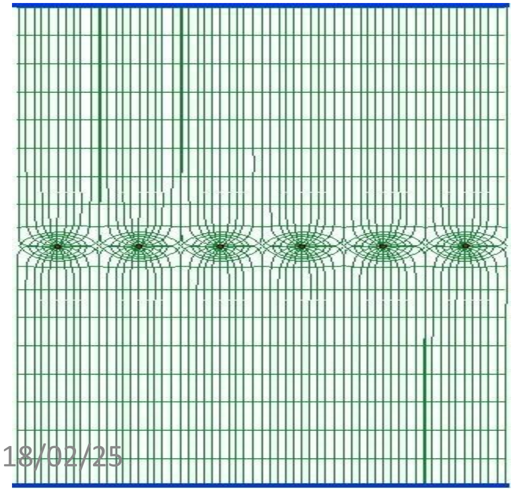
Excellent spatial resolution

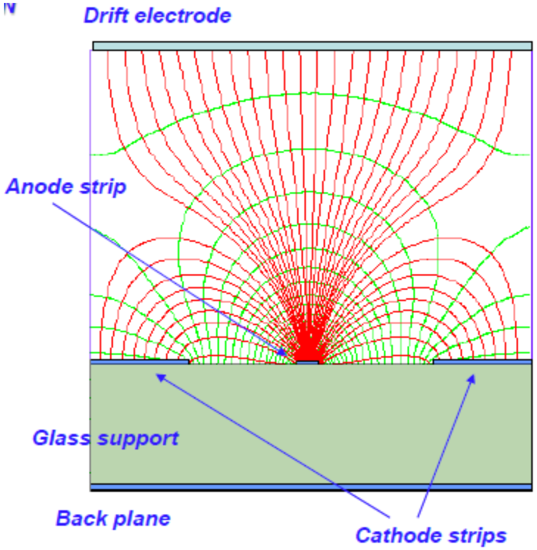




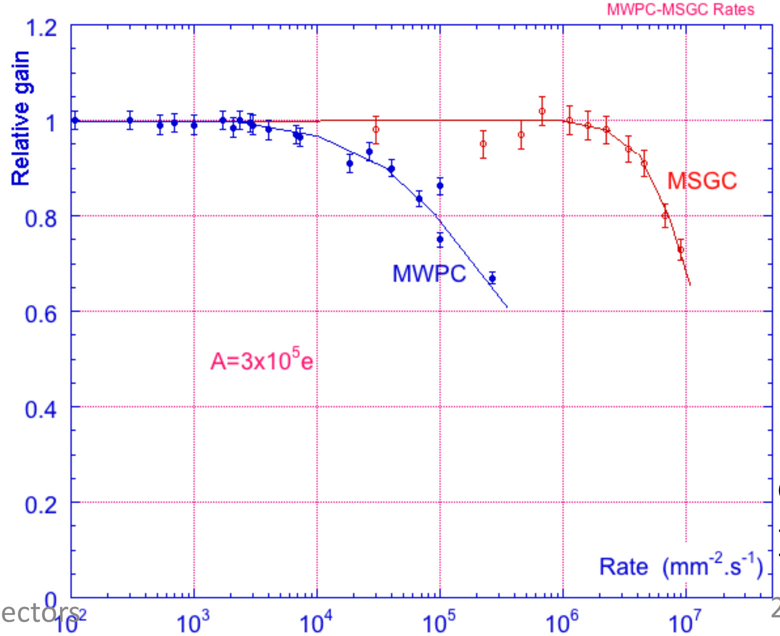
MSGC significantly improves rate capability due to fast removal of positive ions

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





Typical distance between electrodes ~100 μm



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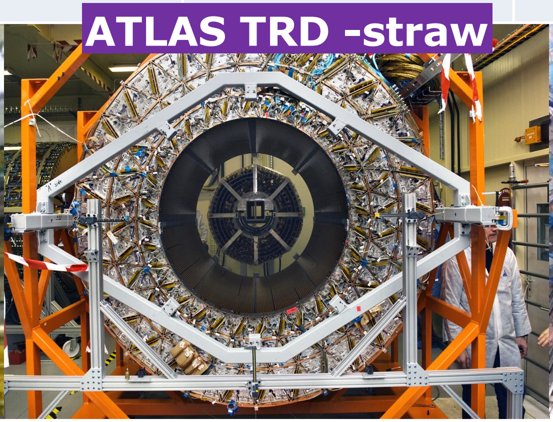
Gaseous Detectors in LHC Experiments

	Vertex	Inner Tracker	PID/ Photon Det.	EM CALO	HAD CALO	MUON Track	MUON Trigger
ATLAS	-	TRD (straws)	-	-	-	MDT, CSC	RPC, TGC
CMS	-	-	-	-	-	DT, CSC	DT, CSC, RPC
TOTEM	-	-	-		-	GEM	GEM
LHCb	-	Straws →SciFi	-	-	-	MWPC	MWPC, GEM
ALICE							

Proven robustness, stability ensure reliable operation for decades (including HL-LHC), supported by aging mitigation, advanced electronics, repair accessibility, and a sustainable approach (environmental-friendly)


CMS DT + RPC


ATLAS TRD -straw

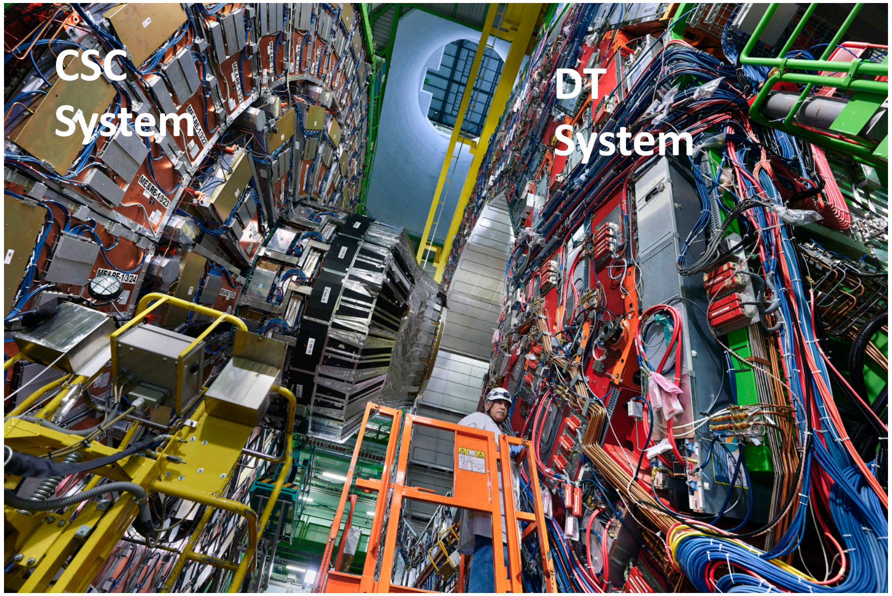

ATLAS TGC


ALICE MRPC

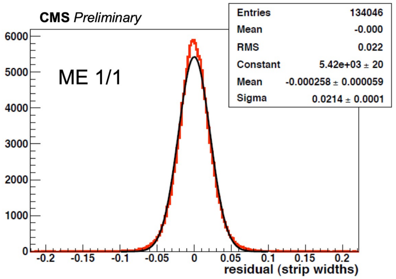
Slide © Anna Colaleo & Maxim Titov

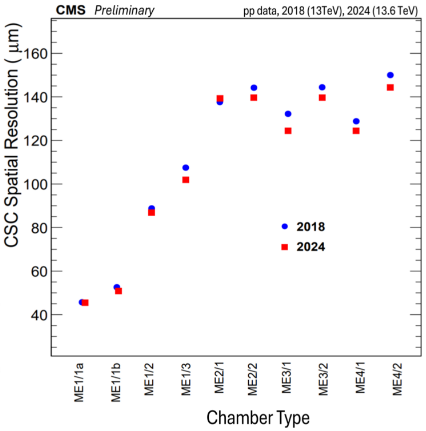
Performance of LHC Wire-based Detectors

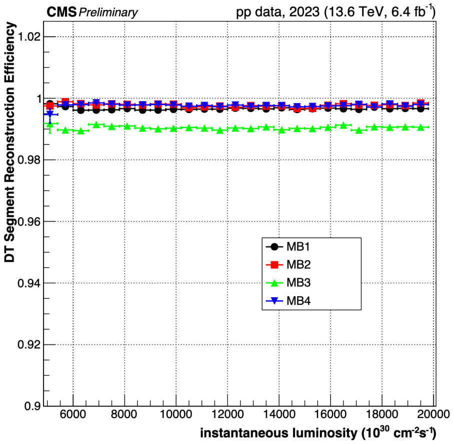
Examples from the CMS Experiment: Drift Tubes & Cathode Strip Chambers

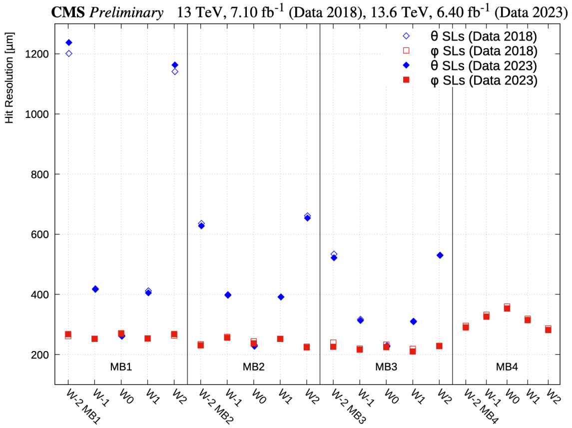


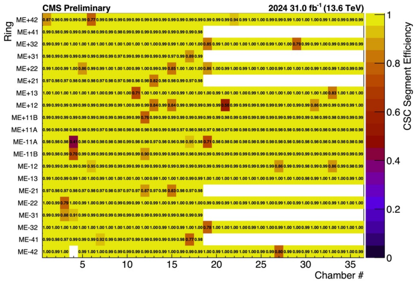
Segment	DT	CSC
# Chambers	250	540
Efficiency	> 99%	> 99%
Spatial Res	250 um	50-150um
Timing Res	2ns	2ns



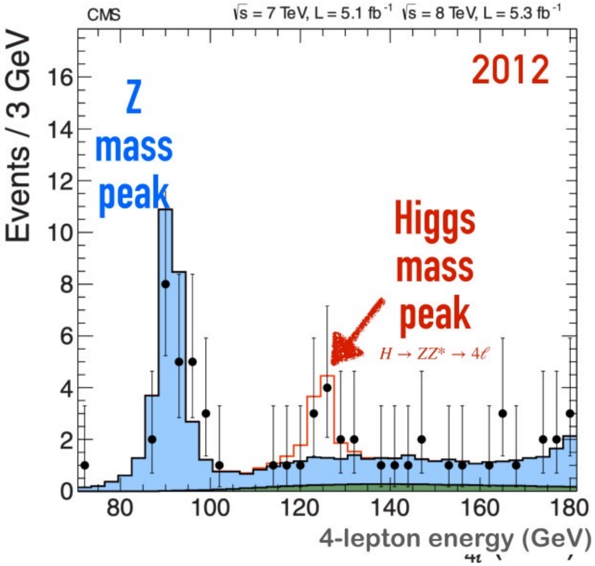


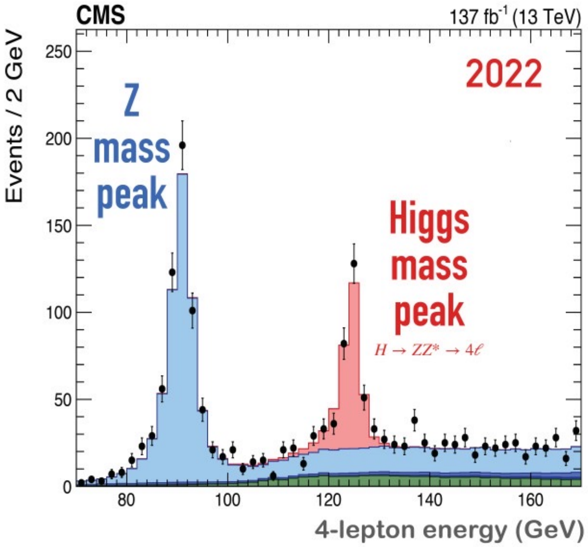






Discovery of the Higgs Boson





2013 Nobel Prize in Physics for Higgs Boson Discovery

AUTHOR INFORMATION

IMPACT FACTOR

3.148

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Journal of Instrumentation

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Higgs Candidates @ LHC Muon gaseous detectors:

$H(ZZ) \rightarrow 4\ell$

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

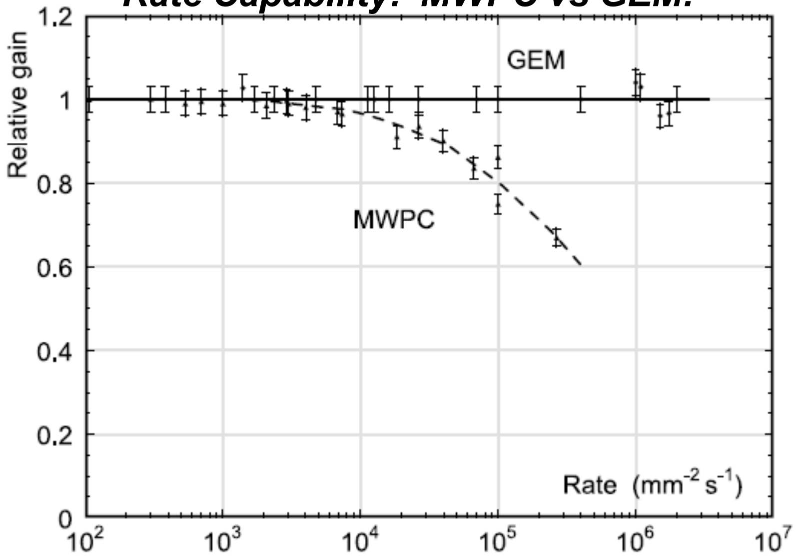
Slide © Maxim Titov

Micro-Pattern Gaseous Detectors - MPGD

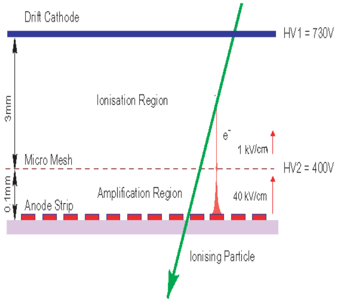
- ✓ ***Micromegas***
- ✓ ***Gas Electron Multiplier (GEM)***
- ✓ ***Thick-GEM (LEM), Hole-Type & RETGEM***
- ✓ ***MPDG with CMOS pixel ASICs (“GridPix”)***

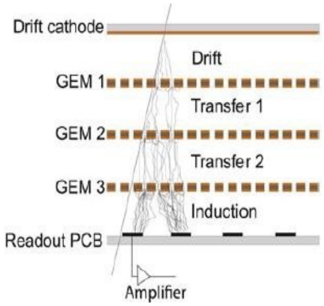
- ✓ ***Micro-Pixel Chamber (μ-PIC)***
- ✓ ***μ-Resistive WELL (μ-RWELL)***
- ✓ ***Resistive-Plate WELL (RPWELL)***

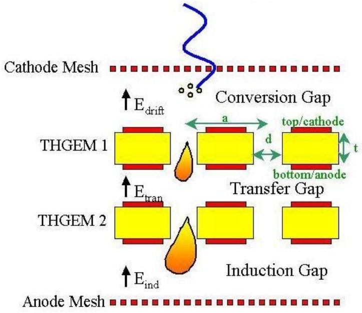
Rate Capability: MWPC vs GEM:

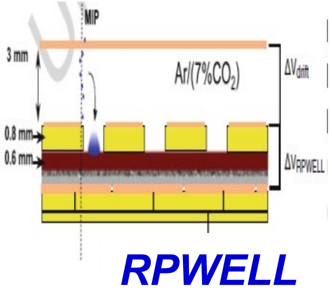


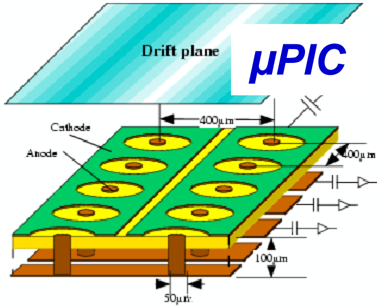
Micromegas ***GEM*** ***THGEM***

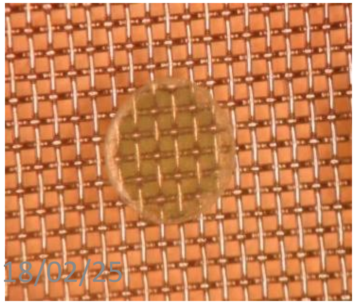


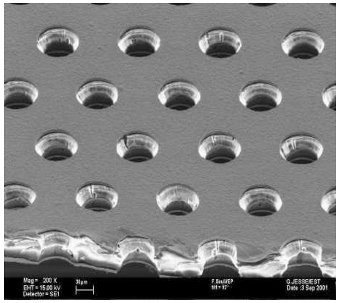


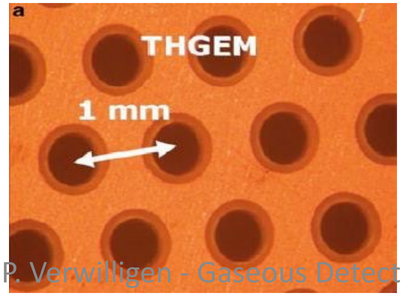


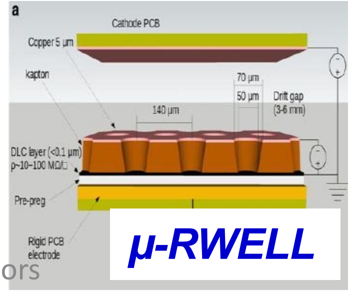


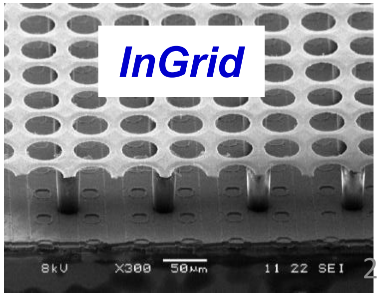












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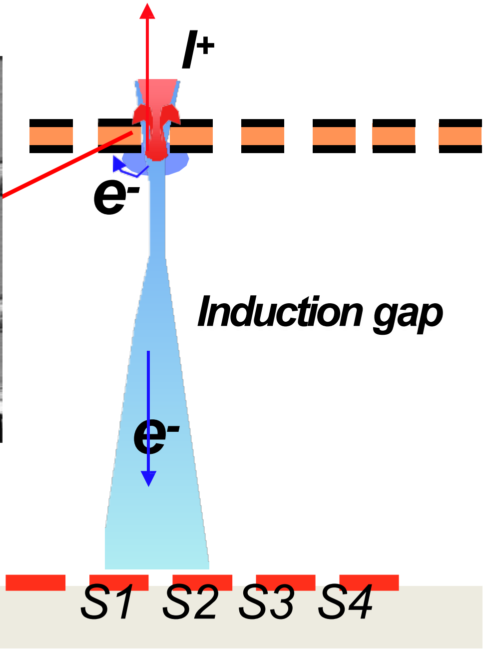
Gas Electron Multiplier - GEM

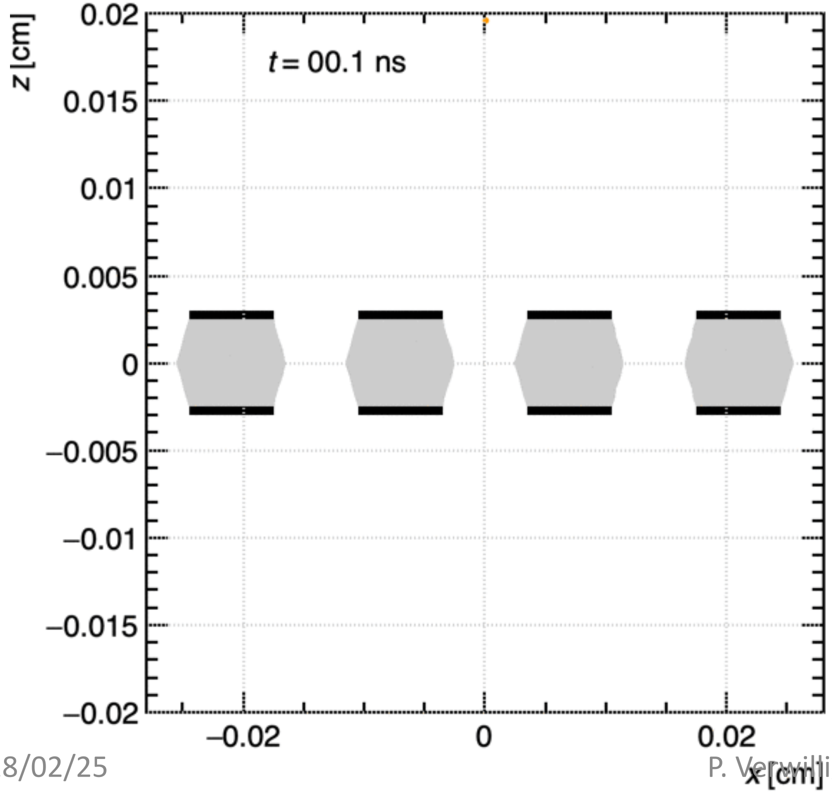
Thin metal-coated polymer foil chemically pierced by a high density of holes

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

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



F. Sauli, NIMA386 (1997) 531

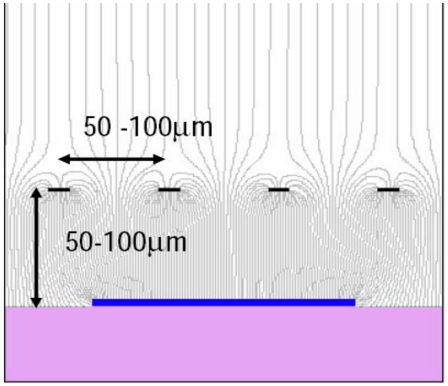


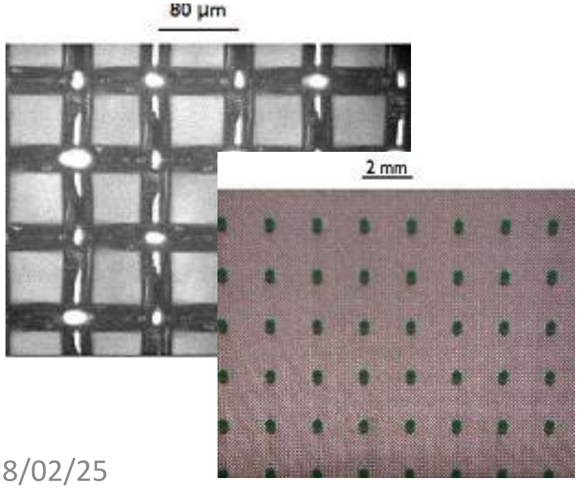
- ✓ Electrons are collected on patterned readout board.
- ✓ A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- ✓ All readout electrodes are at ground potential.
- ✓ Positive ions partially collected on GEM electrodes

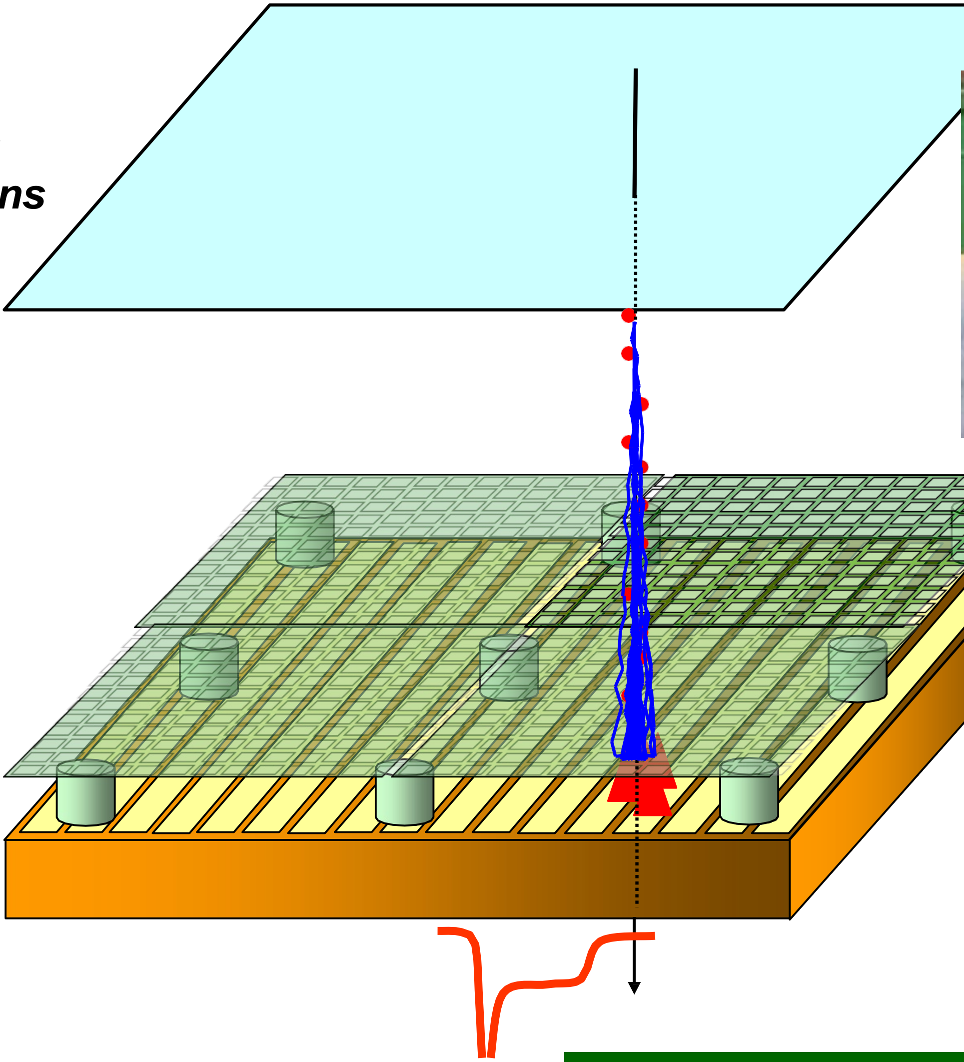
Slide © Maxim Titov

Micro-Mesh Gaseous Structure - MicroMegas

Micromesh Gaseous Chamber:
micromesh supported
by 50-100 mm insulating pillars
Small gap: fast collection of ions







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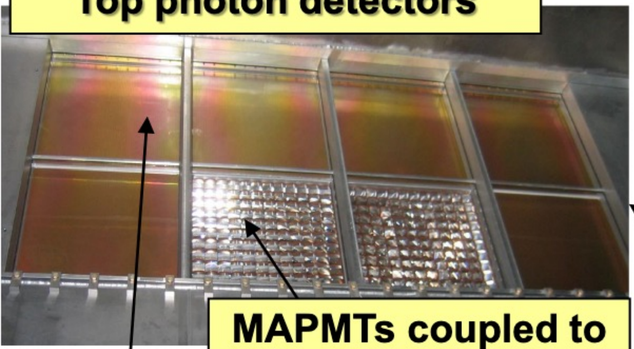
Y. Giomataris, NIMA376 (1996) 29

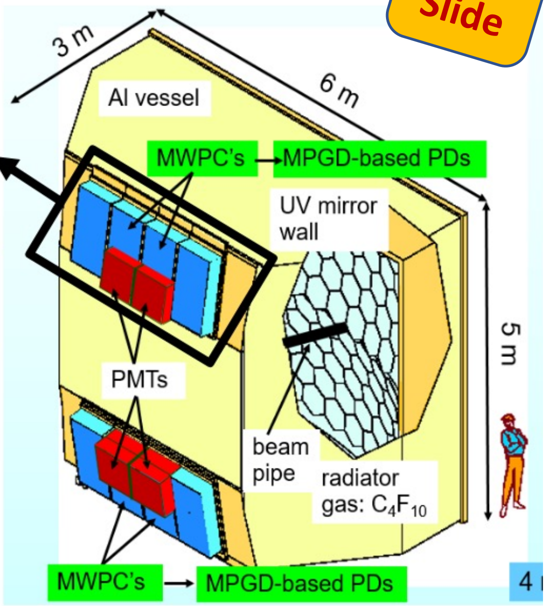
Photon Detection with Hybrid Thick-GEM+MM

Top photon detectors



MAPMTs coupled to lens telescopes

MWPCs+CsI (from RD26): successful but performance limitations, in particular for the 4 central chambers



NEW Slide

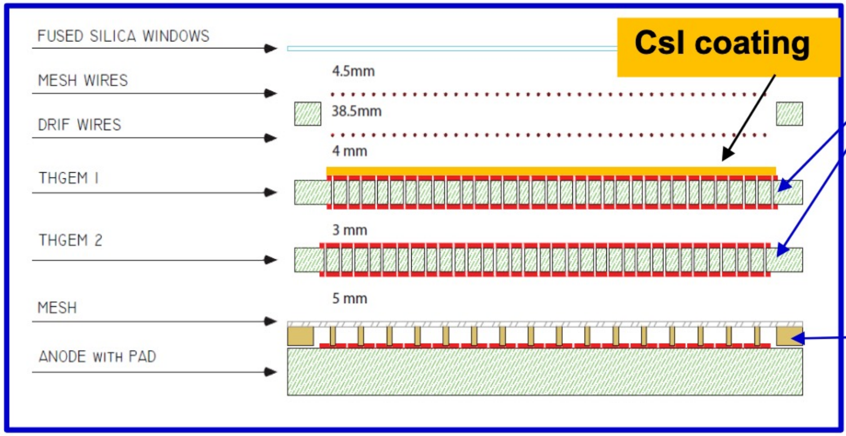
Upgrade of the MWPC-based photon detector of COMPASS

- Need to reach higher rates up to 100kHz/cm2
- Need detector with short signal (avoid long ion drift)

Upgrade: 3-stage hybrid MPGD

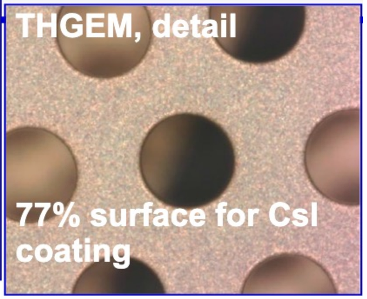
- Double Thick-GEM + Micromegas
- Reflective CsI coating on top of THGEM1 layer

Following a 7-year R&D



2 layers of staggered THGEMs:

- pre-amplification
- transversally enlarged avalanche



THGEM, detail

77% surface for CsI coating

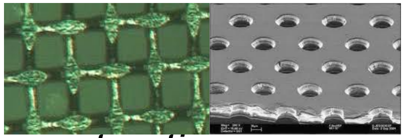
Resistive* MICROMEGAS by *bulk technology

- trapping the ions
- ~100 ns signal formation

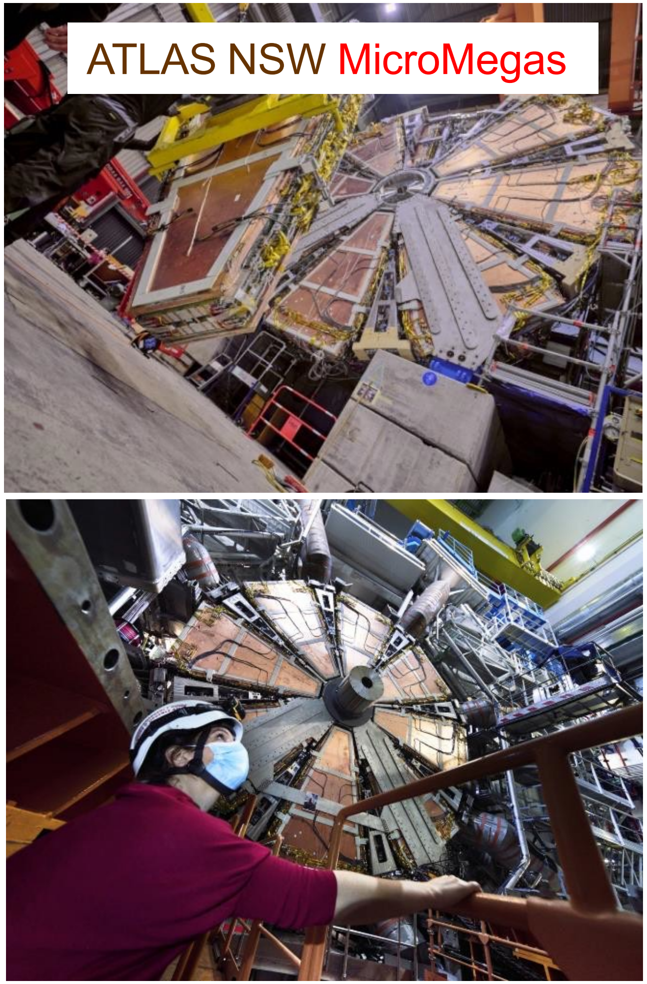
Slide © Silvia Dalla Torre

Future Perspectives on Gaseous Detectors

4. High-Luminosity LHC Upgrades



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


ATLAS NSW MicroMegas


ALICE GEM-TPC


CMS GEM muon endcaps

Slide © Maxim Titov

Gaseous Detector upgrade at the HL-LHC

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300µm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
CMS MUON UPGRADE GE11 CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 50 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 5 kHz/cm^2 **Spatial res.:** 0.6 – 1.2mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 0.18 C/cm^2	Redundant tracking and triggering, improved pt resolution in trigger
CMS MUON UPGRADE GE21 CERN L3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 105 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 1.5 kHz/cm^2 **Spatial res.:** 1.4 – 3.0mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 0.09 C/cm^2	Redundant tracking and triggering, displaced muon triggering
CMS MUON UPGRADE ME0 CERN L3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 65 m^2 Single unit detect: 0.3m^2	**Max. rate**:150 kHz/cm^2 **Spatial res.:** 0.6 – 1.3mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 7.9 C/cm^2	Extension of the Muon System in pseudorapidity, installation behind HGCAL
CMS MUON UPGRADE RE3.1, RE 4.1 2023-24 (CERN L3)	Hadron Collider (Tracking/Triggering)	iRPC	Total area: ~ 140 m^2 Single unit detect: 2m^2	**Max.rate**: 2kHz/cm^2 **Spatial res.:** ~1-2cm **Time res.:** ~ 1 ns **Rad. Hard.:** 1 C/cm^2	Redundant tracking and triggering
LHCb MUON UPGRADE CERN LS4	Hadron Collider (triggering)	µ-RWELL	Total area: ~ 90 m^2 Single unit detector: From 0,4x0,3 m^2 To 0,8x0,3 m^2	**Max.rate**:900 kHz/cm^2 **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ 2 C/cm^2	About 600 detectors
ATLAS MUON UPGRADE CERN LS2 / LS3	Hadron Collider (Tracking/Triggering)	Endcap: Res. Micromegas & sTGC	Endcap area: 1200 m^2 Single unit detect:(2.2x1.4m^2) ~ 2-3 m^2	**Max. rate**:20 kHz/cm^2 **Spatial res.:** <100 µm **Time res.:** ~ 10 ns **Rad. Hard.:** ~ 0.5 C/cm^2	Redundant tracking and triggering; Challenging constr. in mechanical precision
ATLAS MUON UPGRADE (BIS78 PILOT) CERN LS2	Hadron Collider (Tracking/Triggering)	Part of Inner Barrel: RPC + sMDT	Barrel area (3 layers): 140 m^2 Single unit det.: ~ m^2	**Max. rate**:1 kHz/cm^2 **Spatial res.:** ~ 7 mm **Time res.:** ~ 1 ns **Rad. Hard.:** 300 fb	Redundant tracking and triggering; 9 layers with 2D hit position + time
ATLAS MUON UPGRADE (BI PROJECT) CERN LS3	Hadron Collider (Tracking/Triggering)	Inner Barrel RPC	Barrel area: 1400 m^2 Single unit det.: ~ m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.:** ~ (0.1 x 1) cm in (η , ϕ) **Time res.:** ~ 0.5 ns **Rad. Hard.:** 3000 fb	Redundant tracking and triggering; 9 layers with 2D hit position + time

Table © Maxim Titov

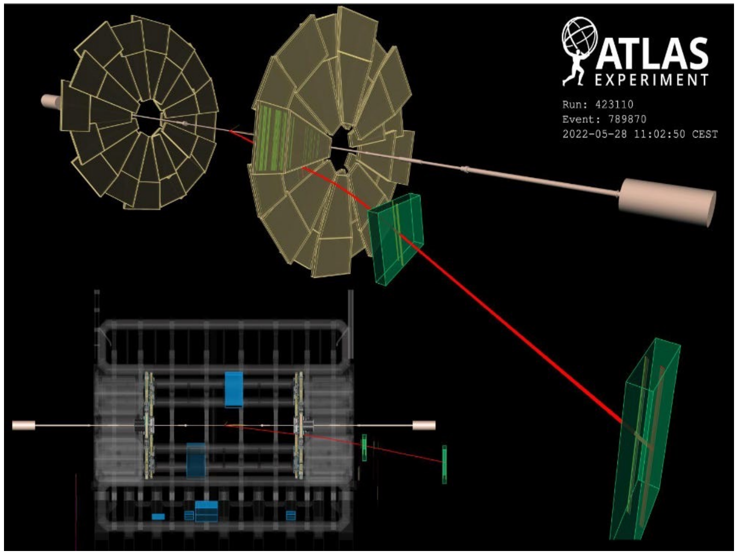
MPGD Upgrades LHC: first experience Run 3

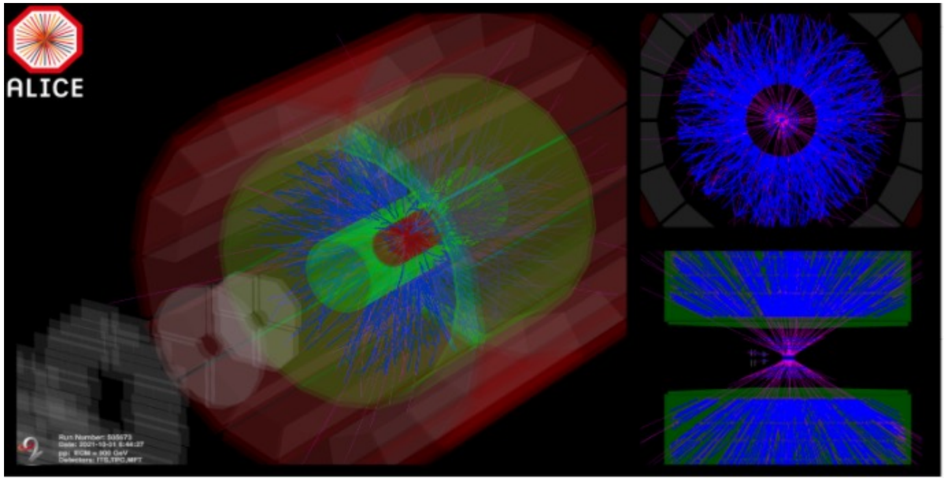
Advancements in MPGDs:

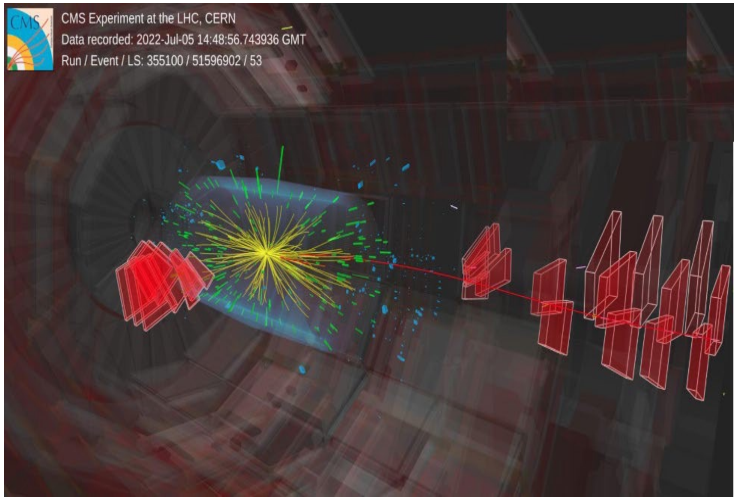
Fuelling ATLAS, CMS, ALICE Upgrades in Run 3

- ATLAS New Small Wheel with Micromegas
- CMS GE1/1 with 3-GEM
- ALICE TPC with 4-GEM readout for TPC

Three ground-breaking LHC upgrades, incorporating MPGDs, embarked on their several year R&D journeys in close collaboration with RD51, leveraging dedicated facilities at the GDD-RD51 Laboratory.







Slide © Anna Colaleo

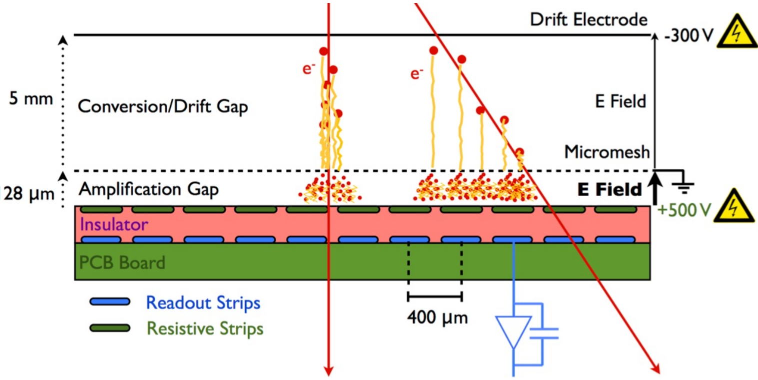
MPGD Upgrades LHC: first experience Run 3

Resistive Micromegas (MM) + small Thin Gap Chambers (sTGCs) for Trigger & Track Reco @ HL-LHC

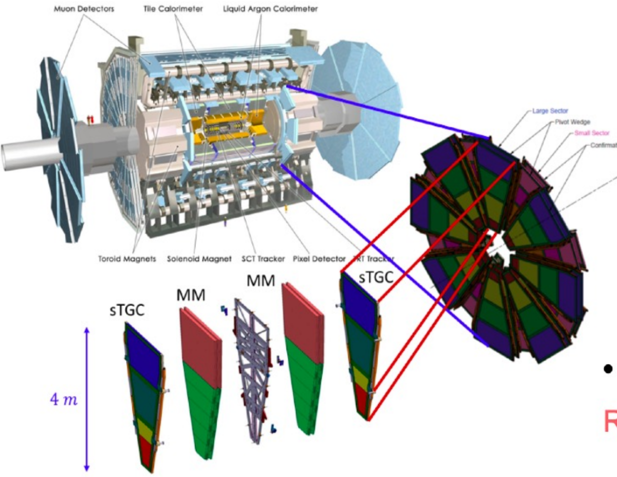
- Precision tracking (~ 100 µm/plane, > 90% efficiency) for $\sigma(p_t/p_t) < 15\%$ at muon $p_T \approx 1$ TeV/c
- particle flux: up to 20 kHz/cm^2 rejecting fake triggers.

Peculiarities of ATLAS NSW Muon Upgrade's Resistive MM:

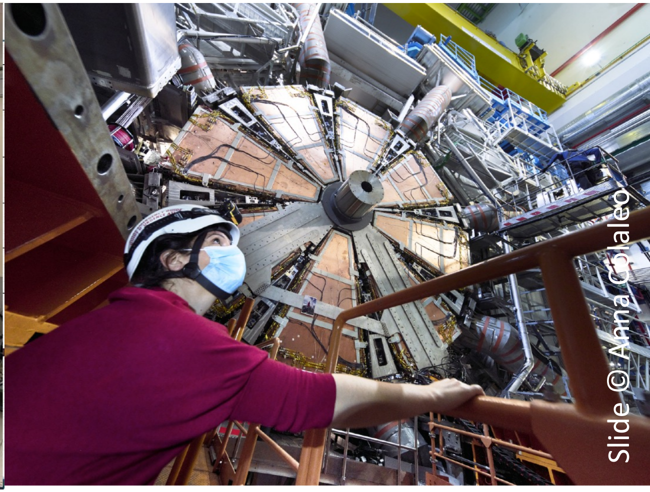
- Screen-printed resistive strips capacitive-coupled to Cu strips.
- Araldite passivation on edges for uniformity, less edge effects.
- Thin metallic micro-mesh at ground potential.
- "Floating" mesh integrated in drift panel
- Operates at -60 V with 93/5/2% Ar/CO2/isobutane mixture.



1200m^2 resistive MM: installation ended beginning of 2022



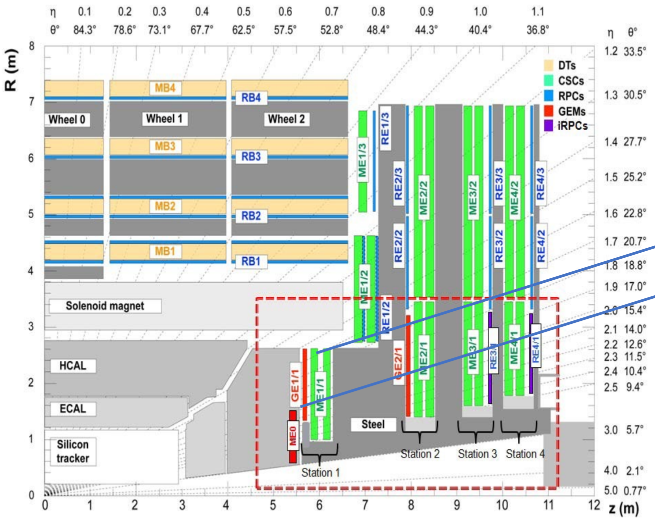
Read-out strip positions need < 30 µm accuracy. Chamber position within 80 µm accuracy.➔ A granite table 8 um precision

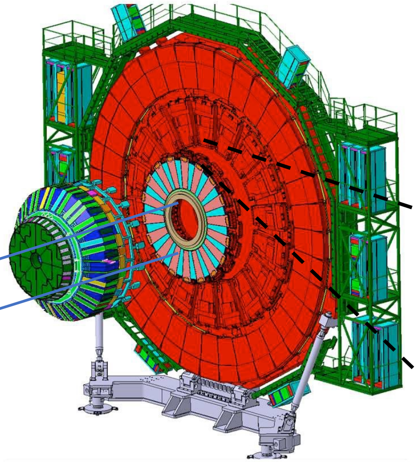


Slide © Anna Colaleo

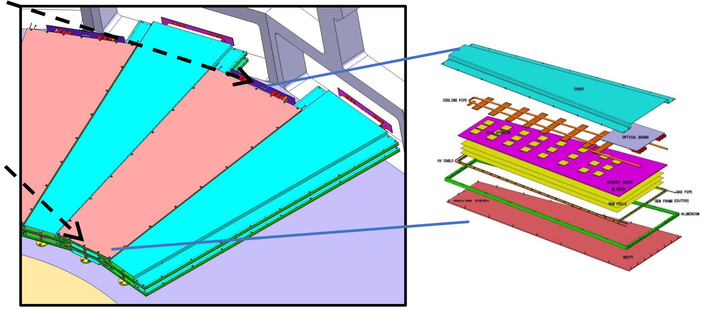
MPGD Upgrades LHC: first experience Run 3

GEM+ Cathode Strip Chambers (CSC) allows for muon momentum measurement in a single station, which helps reduce considerably L1 trigger rate@ HL-LHC





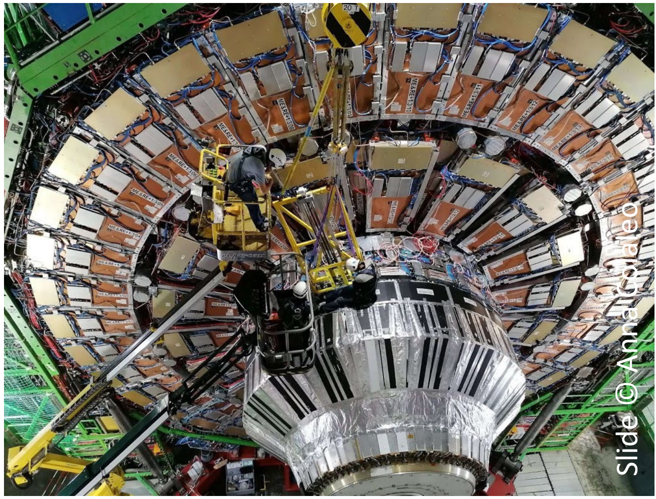
GE1/1: 144 10^0 3-GEM (72 per endcap)$1.55 < |\eta| < 2.18$



CMS triple-GEM detectors peculiarities:

- 3/1/2/1 mm gaps
- <u>Single-mask GEM</u> technology
- <u>mechanical foil stretching technique</u>
- 15-years-long R&D on design, components and materials (longevity, outgassing studies, etc.)
- High-rate O(kHz/cm^2)
- Efficiency > 98%
- Space (time) resolution ≈ 300 μm (8 ns)
- Gas mixt: Ar/CO$_2$ 70/30 (low GWP)

GEM GE1/1 chambers installed: Sept. 2020



Slide © Anna Colaleo

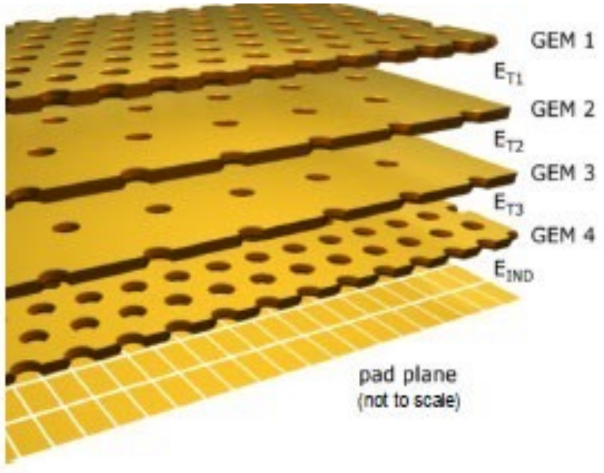
MPGD Upgrades LHC: first experience Run 3

New readout chambers which enables continuous readout@50 kHz in Pb-Pb

➔ choice of 4-GEM

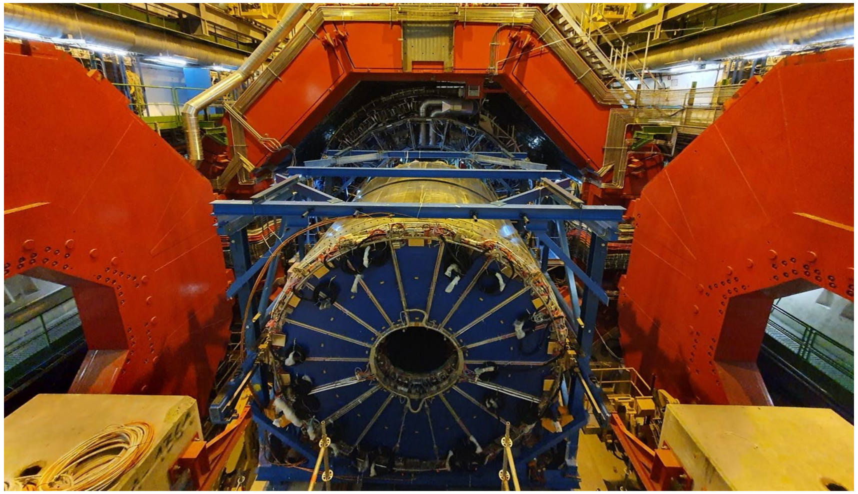
- Total effective gain ~ 2000
- Energy res. σ(E)E < 12%
- Intrinsic ion-blocking capabilities (IB <1%)
- Keep space-charge distortions at a tolerable level
- Mixture Ne-CO2-N2 (90-10-5) (high ion mobility)

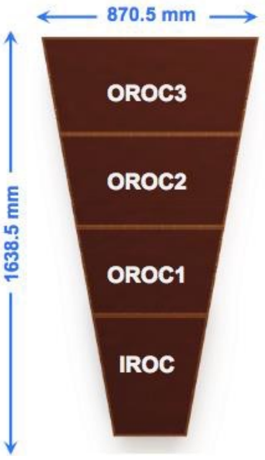
R&D synergies between the ILC TPC and the T2K-II ND TPC.

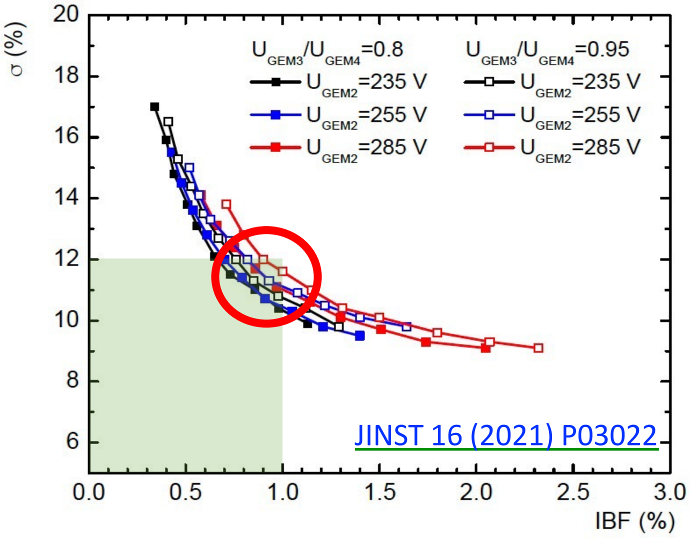


140μm pitch
280 μm pitch
280 μm pitch
140μm pitch

TPC reinstallation in the ALICE cavern (August 2020)







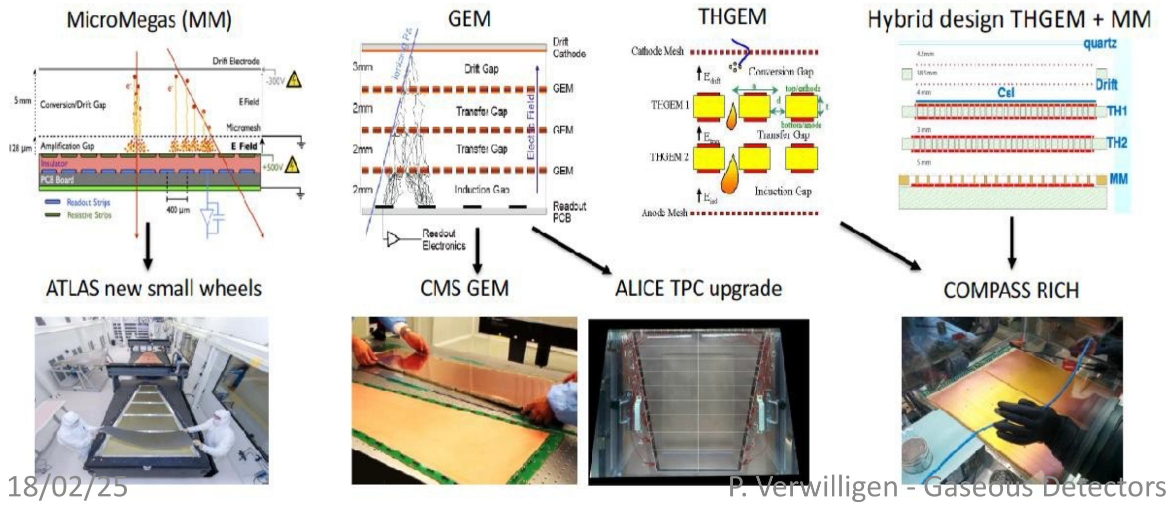
JINST 16 (2021) P03022

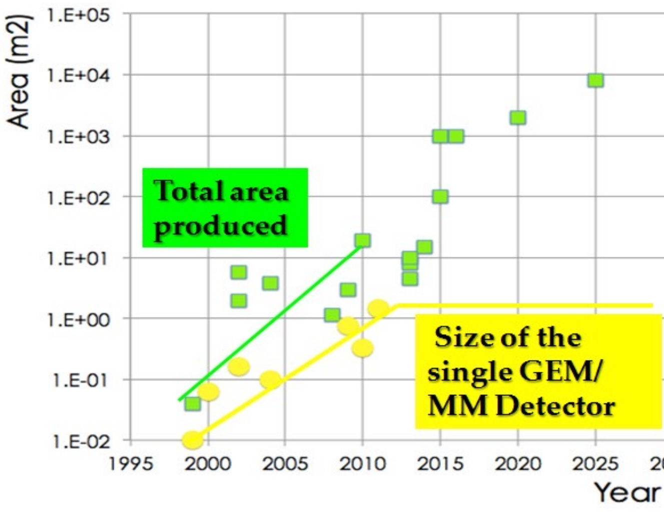
Slide © Anna Colaleo

Success Story: MPGD Technologies @ CERN

- The integration of MPGDs in large experiments was not rapid, despite of the first large-scale application in COMPASS at SPS in the] 2000's
- Scaling up MPGD detectors, while preserving the typical properties of small prototypes, allowed their use in the LHC upgrades
  - ➔ Many emerged from the R&D studies within the CERN-RD51 Collaboration

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS TRACKING > 2002	Fixed Target Experiment (Tracking)	3-GEM Micromegas w/ GEM preampl.	Total area: 2.6 m^2 Single unit detect: 0.31x0.31 m^2 Total area: ~ 2 m^2 Single unit detect: 0.4x0.4 m^2	**Max.rate**: ~100kHz/mm^2 **Spatial res.:** ~70-100µm (strip), ~120µm (pixel) **Time res.:** ~ 8 ns **Rad. Hard.:** 2500 mC/cm^2	Required beam tracking (pixelized central / beam area)
TOTEM TRACKING: > 2009	Hadron Collider / Forward Physics (5.3≤|η| ≤ 6.5)	3-GEM (semicircular shape)	Total area: ~ 4 m^2 Single unit detect: up to 0.03m^2	**Max.rate**:20 kHz/cm^2 **Spatial res.:** ~120µm **Time res.:** ~ 12 ns **Rad. Hard.:** ~ mC/cm^2	Operation in pp, pA and AA collisions.
LHCb MUON DETECTOR > 2010	Hadron Collider / B-physics (triggering)	3-GEM	Total area: ~ 0.6 m^2 Single unit detect: 20-24 cm^2	**Max.rate**:500 kHz/cm^2 **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ C/cm^2	Redundant triggering
COMPASS RICH UPGRADE > 2016	Fixed Target Experiment (RICH - detection of single VUV photons)	Hybrid (THGEM + CsI and MM)	Total area: ~ 1.4 m^2 Single unit detect: ~ 0.6 x 0.6 m^2	**Max.rate**:100 Hz/cm^2 **Spatial res.:** <~ 2.5 mm **Time res.:** ~ 10 ns	Production of large area THGEM of sufficient quality
ATLAS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	Resistive Micromegas	Total area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**Max. rate**:15 kHz/cm^2 **Spatial res.:** <100µm **Time res.:** ~ 10 ns **Rad. Hard.:** ~ 0.5C/cm^2	Redundant tracking and triggering; Challenging constr. in mechanical precision
CMS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.:** ~100µm **Time res.:** ~ 5-7 ns **Rad. Hard.:** ~ 0.5 C/cm^2	Redundant tracking and triggering
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300µm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution





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RD51 Collaboration Legacy 2008 - 2023

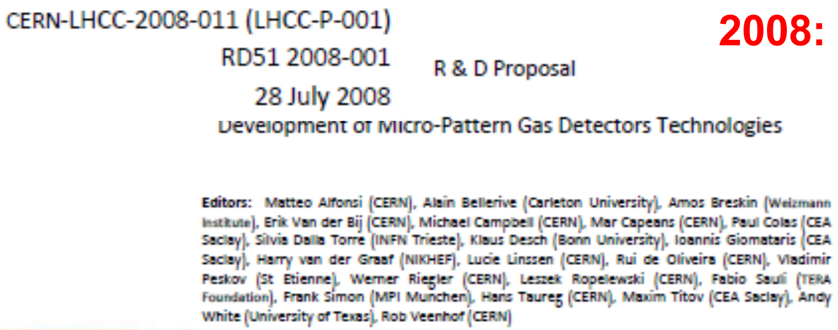
RD51 CERN-based "TECHNOLOGY - DRIVEN R&D COLLABORATION" *was established to advance MPGD concepts and associated electronics readout systems*

RD51 community: ~ 90 institutes, 500 members

RD51

renewed for 3rd term 2019-2023

2008:

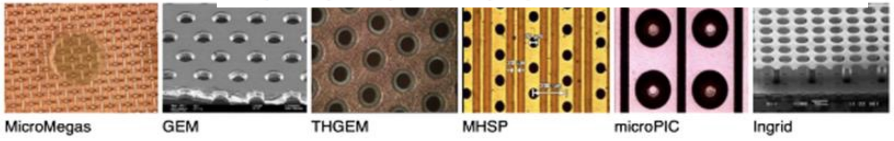


CERN-LHCC-2008-011 (LHCC-P-001)
RD51 2008-001
28 July 2008

R & D Proposal

Development of Micro-Pattern Gas Detectors Technologies

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



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

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

2018:

May 2018

R&D PROPOSAL
RD51 EXTENSION BEYOND 2018

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

Abstract

arXiv:1806.09955v1 [physics.ins-det] 26 Jun 2018

arXiv:1806.09955

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

Slide © Maxim Titov

RD51 Collab legacy: “the RD51-Model”

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

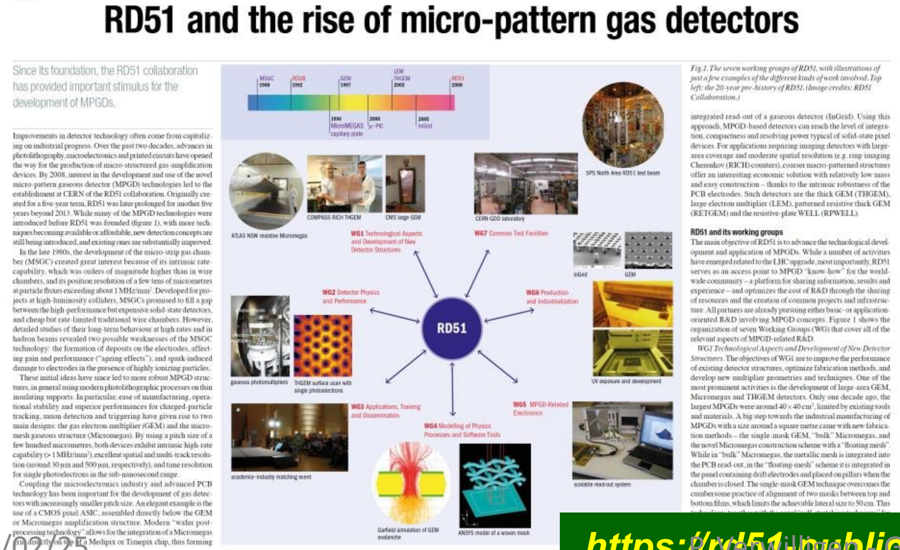
RD51:

3 MAJOR ASSETS

Scientific organisation in 7 working groups

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

CERN Courier (5 pages) Volume, October 2015



RD51 and the rise of micro-pattern gas detectors

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

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 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 the micro-mesh gaseous structure (Micromegas). By using a pitch size of a few hundred micrometres, both devices exhibit intrinsic high-rate capability (> 1 MHz/mm^2), excellent spatial and multi-track resolution (around 30 μm and 500 μm, 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 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 worldwide 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 × 40 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 “bulk” Micromegas, the metallic mesh is integrated into the PCB read-out, in the “floating-mesh” scheme it 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

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.)

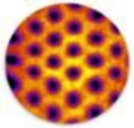
Community and Expertize (RD51 Scientific Network)

CERN GDD team

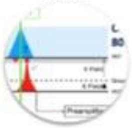
RD51 groups

MPGD Technology Development & Dissemination

Detector physics



Generic R&D



Industrialisation

Meetings & conferences

Common Projects

R&D Tools, Facilities and Infrastructure

Common lab

Test beams

Electronics

Simulation tools

MPT workshop

Thin film lab

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

Future Perspectives on Gaseous Detectors

5. R&D on Gaseous Detectors: towards a long-term detector R&D plan

2019
Granada Symposium
WGs and Physics Briefing Book

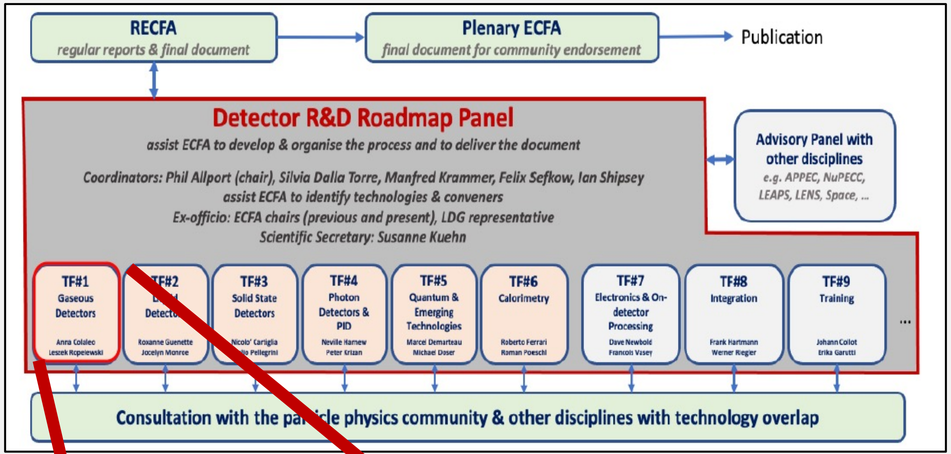
2020
ESPP update
HEP strategic projects

2021
ECFA detector R&D roadmap
TF & community workshops

2023
ECFA DRD proposals

2025
DRD MoUs
collaborations active

2026-27
ESPP update



10 Global Recommendations
GR4: international coordination & organization of R&D activities
GR6: establish long term strategic funding program
↓
Form international DRD collaborations
hosted at CERN (CERN/SPC/1190)

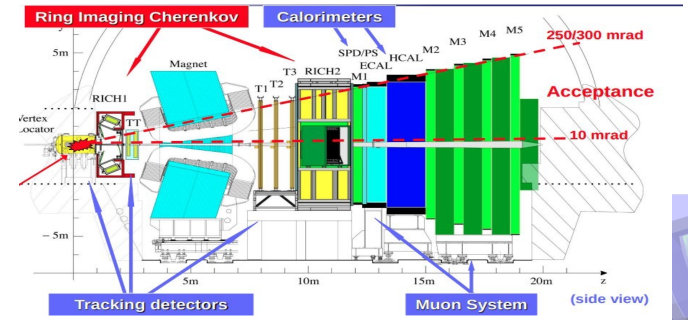
Conveners: Anna Colaleo (INFN-Bari), Leszek Ropelewski (CERN)

Experts: Klaus Dehmelt (SUNY), Barbara Liberti (INFN-Rome2), Maxim Titov (CEA Paris-Saclay), Joao Veloso (Univ. Aveiro)
Link to the coordination team : Silvia Dalla Torre (INFN-Trieste)

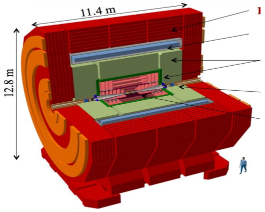
Slide © Anna Colaleo

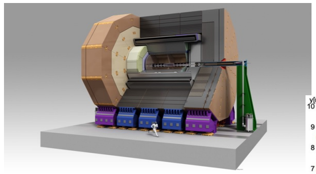
Main Targets of Gaseous Detector R&D

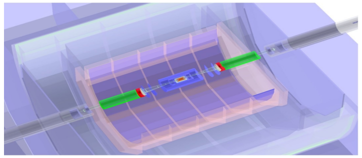
HL-LHC after LS4

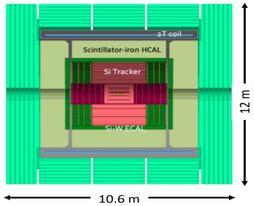


Higgs Factories

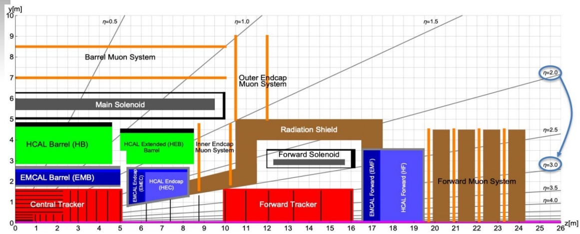




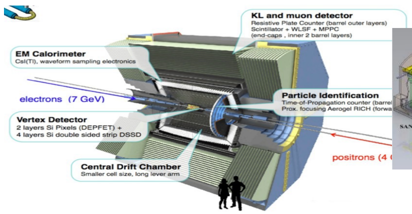


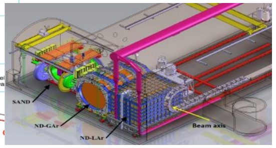


Future hadron colliders (FCC-hh/eh colliders)



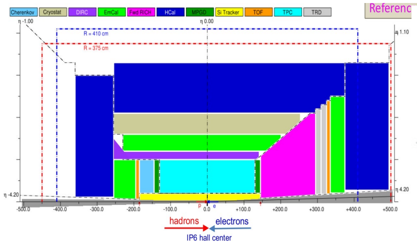
SuperKEKB, DUNE ND



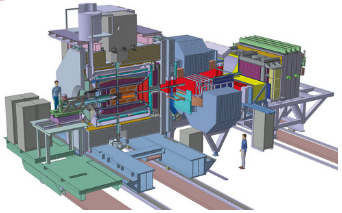


Hadron physics

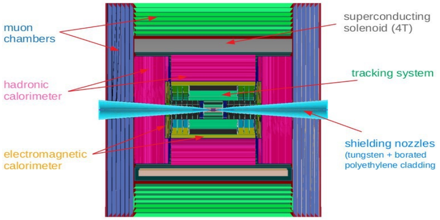
EiC



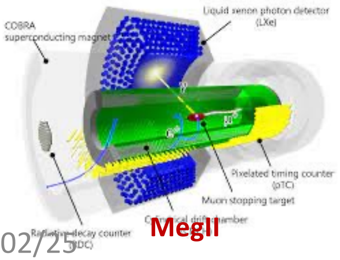
PANDA



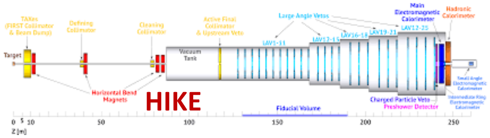
Muon Collider



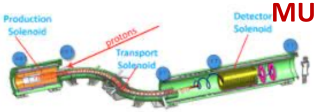
Rare event search, fixed target (LFV, Kaon physics)



MegII



HIKE



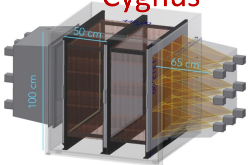
MU2E

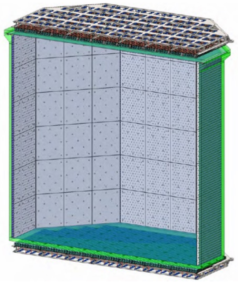
DM, solar axions, ββ0ν-decay, neutrino, nuclear, astroparicle

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Darksphere

Cygnus



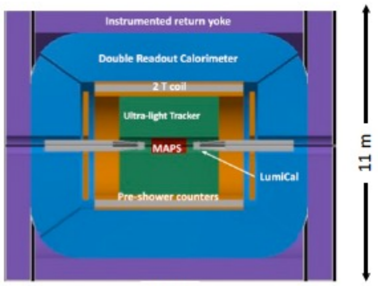


DarkSide20 and ARGO

Slide © Anna Colaleo

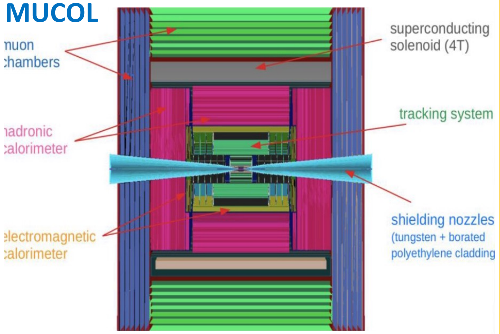
Muon Detector for FCC-ee / CEPC / MuColl

IDEA



New, innovative, possibly more cost-effective concept
- Silicon vertex detector
- Short-drift, ultra-light wire chamber
- Dual-readout calorimeter
- Thin and light solenoid coil inside calorimeter system
- 3 muon stations in the return yoke

MUCOL



Based on CLIC detector design; technology developments carried out for LCs
- All silicon vertex detector and tracker
- 3D-imaging highly-granular calorimeter system
- Coil outside calorimeter system
- 6-7 muon stations in the return yoke

3-6 Muon Stations

Space resolution, σ_x, of O(100)um

Efficiency ~ 98-99%

Time resolution: few ns: trigger/BX-id

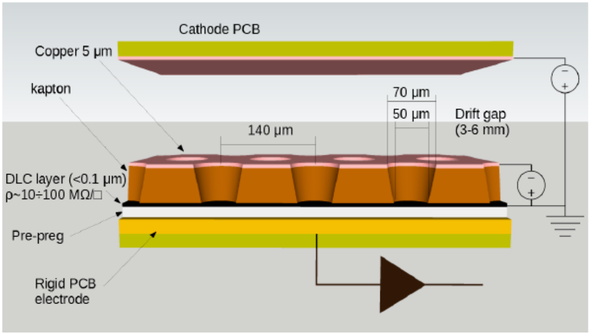
Rate: few KHz/cm² – MHz/cm²

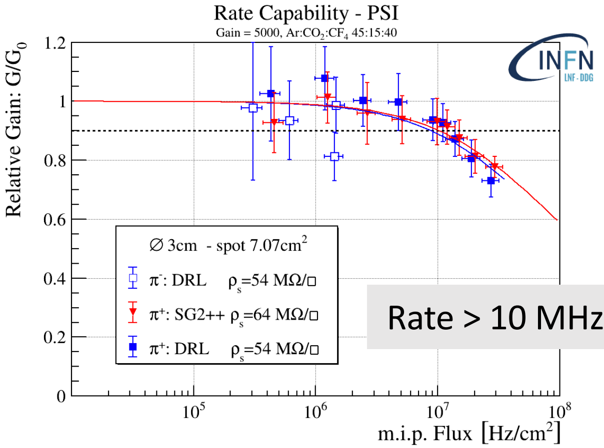
Low GWP gas mixture

- RPC -30 × 30 mm² cells @CLD/CEPC
- MPGD/RPC@ Muon collider
- µRWell 50x50 cm² (tiles) also for pre-shower @FCC

G.Bencivenni

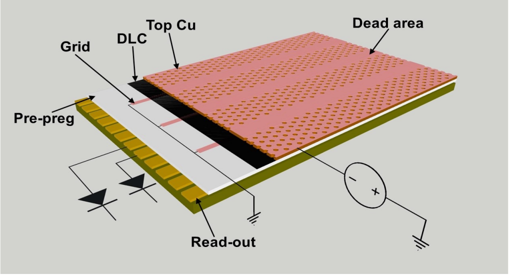
µRWell



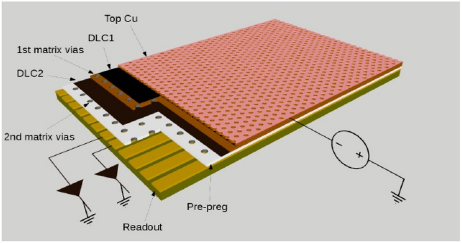


Rate > 10 MHz/cm²

@High Rate: Different Grounding schema for fast current evacuation at high rate



Silver Grid (SG)
- Single DLC layer grounded by condutive strip lines realized on ttop of he DLC layer)

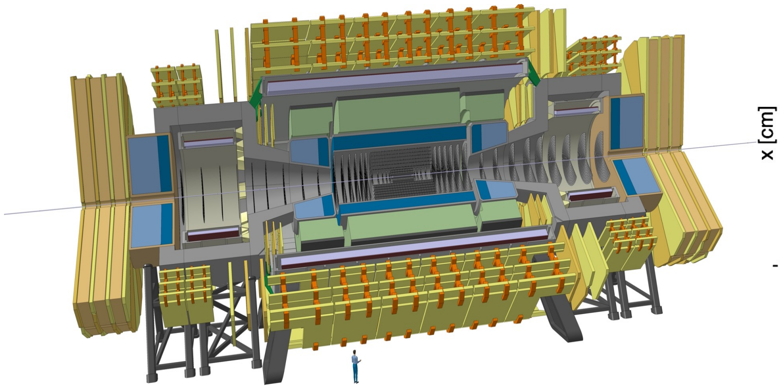


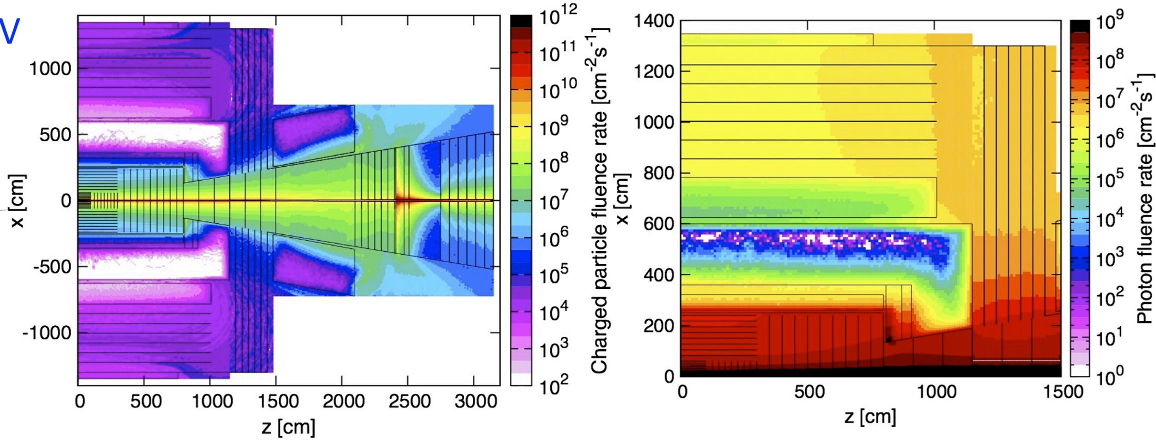
Double resistive layer (DRL)
- Double DLC layers connected through matrics of conductive vias to the readout electrodes

Slide © Anna Colaleo

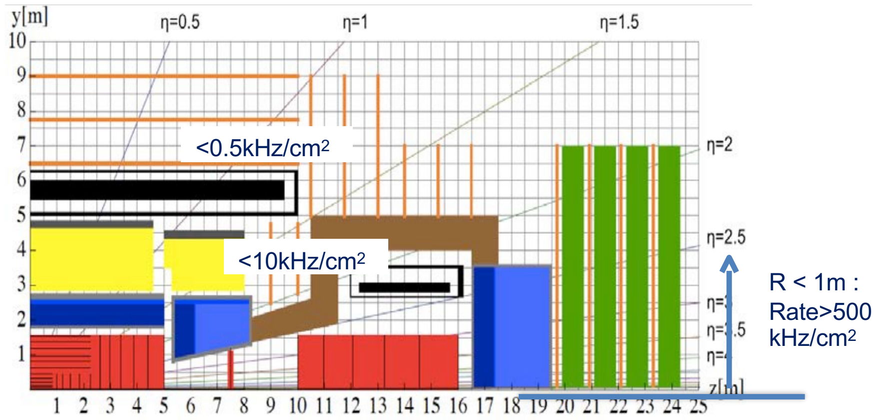
Muon Detector for FCC-hh

Muon System, tracking and trigger capabilities with resolution of 50 um, $\sigma_{p_T}/p_T \approx 5\%$ at 10TeV





- Barrel Muon system (2 layers) : 2000 m^2
- Endcap Muon System (2 layers): 500 m^2
- Forward Muon System: (4 layers): 320 m^2



R < 1m : Rate>500 kHz/cm2

Hardest challenge

- pp collisions at 100 TeV (FCC-hh)
- Pileup: 1000 events/bunch crossing → spatial resolution, timing

Muon barrel and endcap

- Charged rates ~ 5x10^{4} cm^{-2}s^{-1}
- photon rates ~ 5x10$^{6-8}$ cm^{-2}s^{-1}
- N fluence ~10^{14} cm^{-2} ➔ shielding can mitigate effect

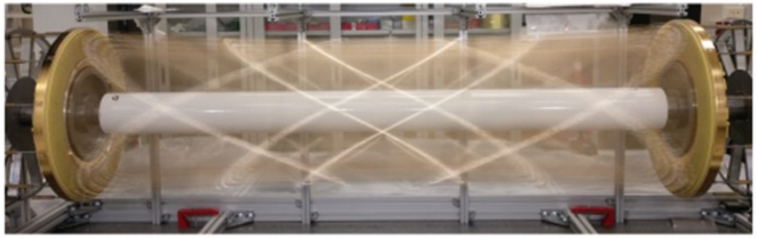
- Current muon system gas detector technology will work for most of the FCC detector area
- Forward region (r < 1 m) ➔ more R&D would be needed

Slide © M.Aleksa & G.Aielli

Drift Chambers for FCC-ee / CEPC

The IDEA drift chamber (DCH)

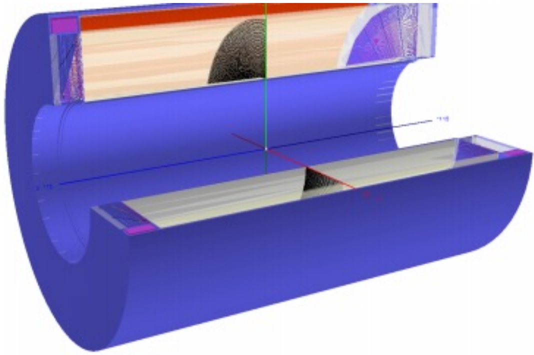
Approach at construction technique of high granularity and high transparency Drift Chambers



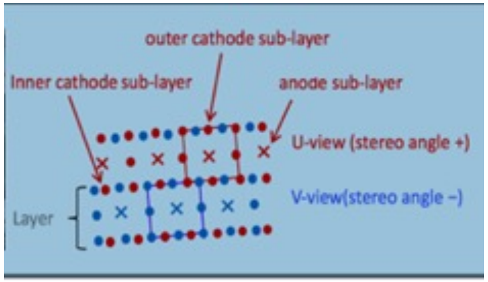
sense wires:	20 mm diameter W(Au) =>	56448 wires
field wires:	40 mm diameter Al(Ag) =>	229056 wires
f. and g. wires:	50 mm diameter Al(Ag) =>	58464 wires
	343968 wires in total	

The wire net created by the combination of + and – orientation generates a more uniform equipotential surface

- High wire number requires a non standard wiring procedure and needs a feed-through-less wiring system.
- A novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

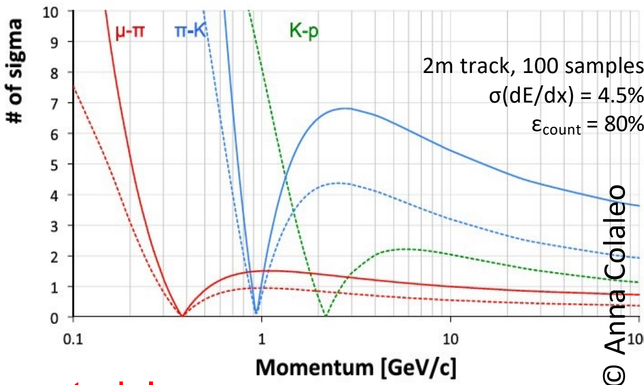


- ☐ GAS: 90% He – 10% iC_4H_{10}
- ☐ Radius 0.35 – 2.00 m
- ☐ Total thickness: 1.6% of X_0 at 90°



- Large number of channels,
- gas gains ~5×10^5
- long drift times (slow drift velocity),
- trigger rate (Z_0-pole at FCC-ee) = 25kHz/cm²

Particle Separation (dE/dx vs dN/dx)



Slide © Anna Colaleo

The dE/dx < 3% , momentum resolution: σ(pT)/pT ≈ 0.4% at 100 GeV/c with cluster counting, a desirable achievement :

- on-line real time data reduction algorithms
- new wire material studies
- new wiring systems for high granularities/ new end-plates / new materials

Inner/Central Tracking with PID: Straw Tubes

Self-supporting straw tubes with thin anode wire and an aluminised Mylar cathode wall offers a combination of short drift time, low mass, and high spatial resolution tracking by using long (a few meters) and small diameter (< 1 cm) straws, arranged in planar layers.

Innovative straw detectors are foreseen at both future storage rings and fixed target facilities.

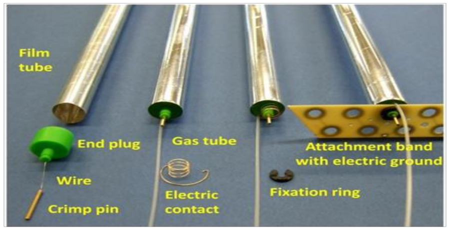
NA62 is the state-of-the-art straw tracker

- New ultrasonic welding technique to close the straw and to keep them straight and withstand the vacuum pressure without breaking
- rates up to 40 kHz/cm (500 kHz/straw), ageing resistance up to ~ 1 C/cm/wire
- material budget of a straw module ~ 0.7% X/X_0

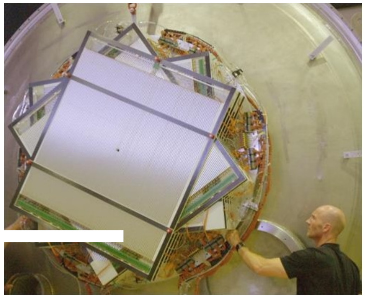
	TOF-STT [5] (COSY)	PANDA STT/FT (FAIR)	NA62 [3] (CERN-SPS)	COMET [6] (J-PARC)	COMET+	SHiP [7] (CERN-SPS)
Mylar wall	32 µm*	27 µm*	36 µm	20 µm	12 µm	36 µm
Winding	helical, 2 strips glued		longitudinal ultrasonic welding			
Manufacturer	Commercial (LAMINA, UK)		JINR, Dubna			
Tube diam.	10.0 mm	10.0 mm	9.8 mm	9.8 mm	5.0 mm	20 mm
Cathode	Al (30 nm)	Al (100 nm)	Cu/Au (50/20nm)	Al (70nm)	Al (70nm)	Cu/Au (50/20nm)
Tube length	1050 mm	1400 mm	2100 mm	600 -1100 mm		5000 mm
Straw no.	2704	4224 / 12224	7168			16000
In vacuum	yes	no	yes	yes	yes	yes
Status	Exp. finished (2009-2013)	Prod. ongoing, exp. in 2025	Experiment ongoing	Production completed	In develop-ment	Planned
Specific R&D	Vacuum tracker	Low X/X0 solenoid tracker	Vacuum tracker	Thinnest wall vacuum tracker		Long straws in vacuum

Table © Peter Wintz

Straw tube components (for PANDA-STT
1.2% X/X0, spatial resolution~150 µm




NA62 Straw station

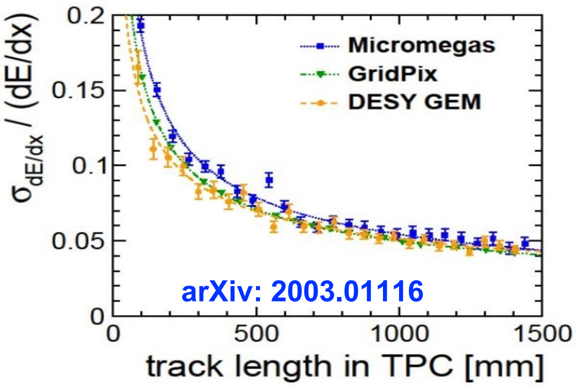

COSY-TOF Straw tracker

Slide © Anna Colaleo

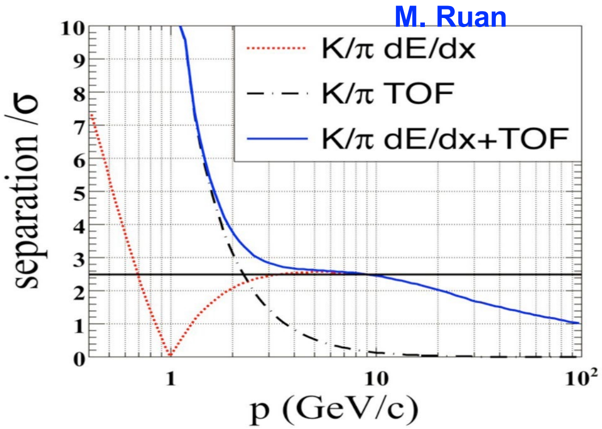
Inner/Central Tracking with PID: TPC + MPGD

ILC-TPC: Target requirement: point resolution 100 um in transverse plane and dE/dx resolution < 5% reached with all technologies (**GEM, MM and GridPix**)

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

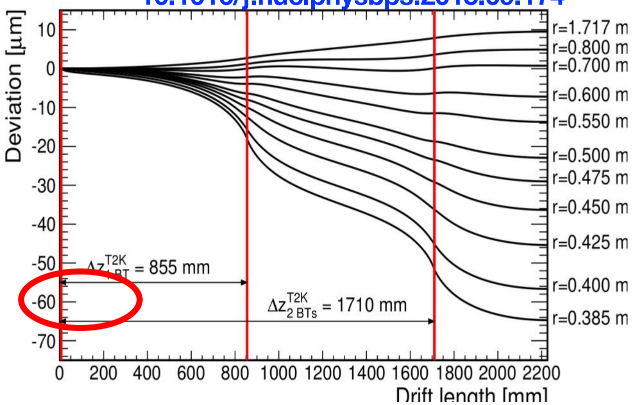


arXiv: 2003.01116



M. Ruan

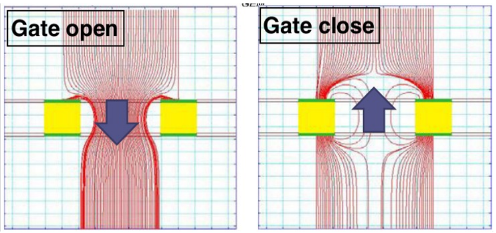
10.1016/j.nuclphysbps.2015.09.174



Track Distortions in ILC TPC @ 250 GeV (L~10^{34} cm^{-2}), 3.8 T

beam-beam effects are dominant: primary ion density 1-5 ions/cm^3 ➔ track distortions < 5 μm

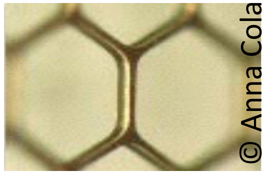
Gas amplification 10^3 ➔distortions of 60 μm ➔ gating device is needed



➔ Exploit ILC bunch structure as 1 ms long bunch trains will arrive every 200 ms

Gating GEM gate opens 50 us before the 1st bunch and closes 50 us after the last bunch:

- Measured electron transparency >80 % (as in simulations) for ΔV ~ 5V

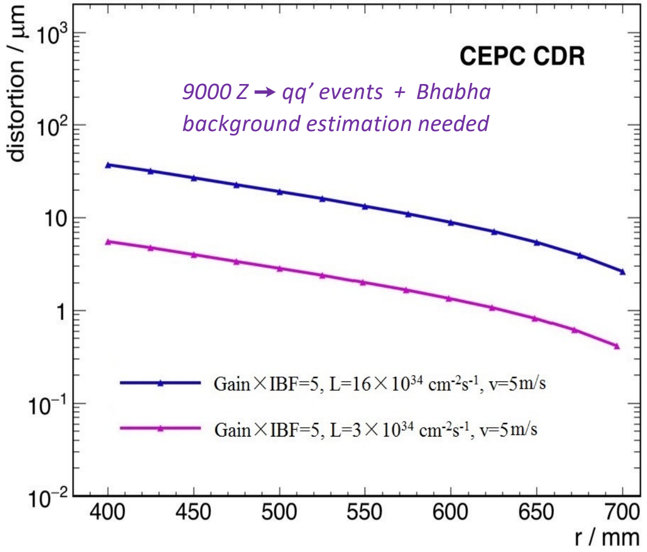


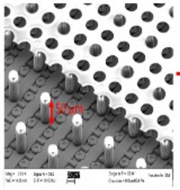
Slide © Anna Colaleo

Inner/Central Tracking with PID: TPC + MPGD

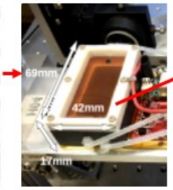
CEPC/FCC: No bunch structure ➔ continuous beam (cfr. ALICE)

- **HZ/WW/tt running➔** Pad readout (MM + GEM)
- **Z pole running**(@10^{36}): primary ion density 1000 ions/cm^3
  ➔ tracks distortions O(mm) ➔ Pixelated readout ➔ GridPix
  - ✓ Single ionisation electrons are detected with high efficiency
  - ✓ dE/dx by cluster counting
  - ✓ Measuring IBF for Gridpix is a priority, expected $\mathcal{O}$(1‰)

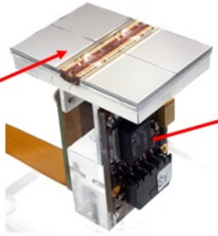




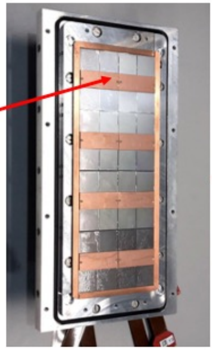
MM grid (InGrid) on Timepix chip



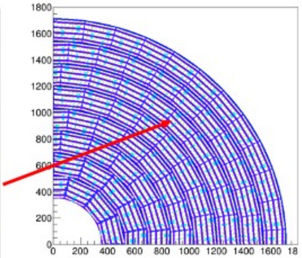
Single chip 2017



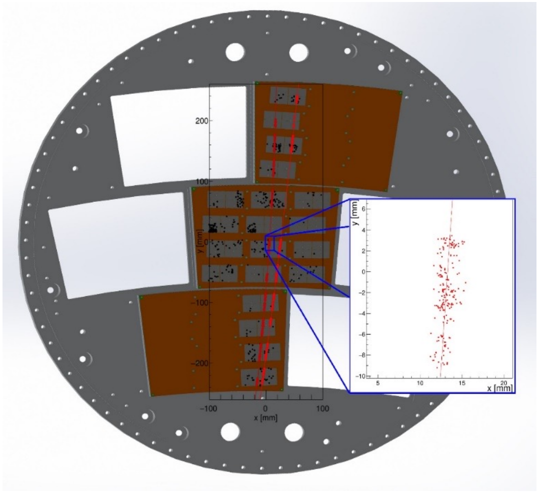
Quad 2018



Module - 2019



TPC plane



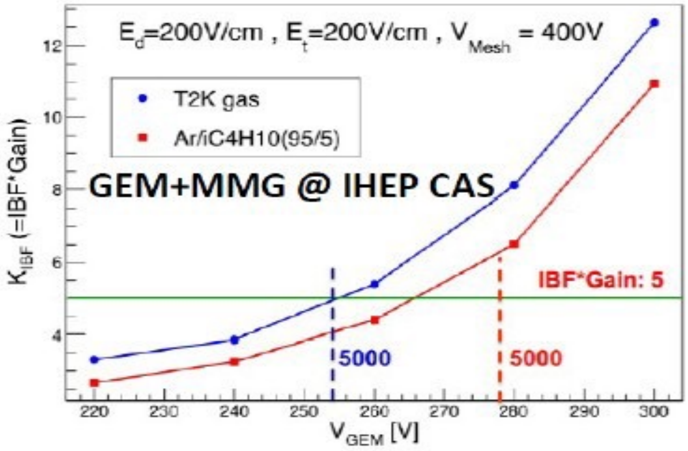
The maximum possible information from a track is acquired:

50 cm track length with ~ 3000 hits

→ each is electron from the primary ionisation

→ for track reconstruction, in case of curved tracks

Micromegas + GEM studies for CEPC / FCC-ee to minimize ion backflow

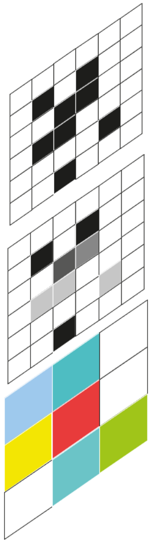


Slide © Anna Colaleo

Hadron Calorimetry: Steel abs + RPC/MPGD

The Particle-flow approach

- high granularity (σ_{xy} = 50um, σ_t = 5ns) at low cost
- Low pad multiplicity
- radiation hard detector
- good energy resolution, bkg rejection:

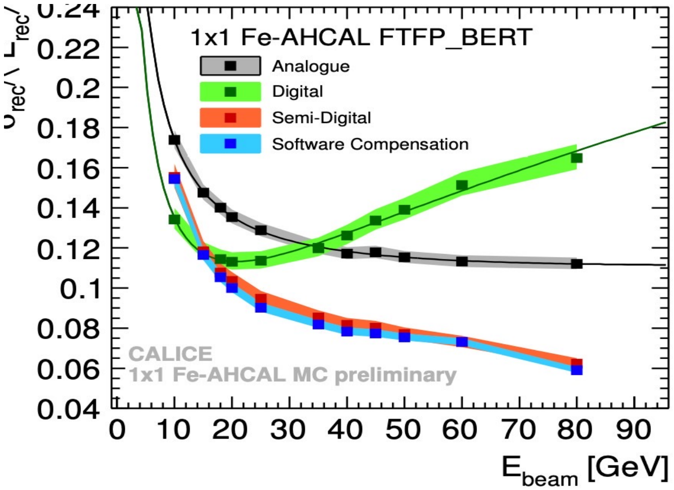


"digital"
counting hit cells

"semi-digital"
2 bits per cell:
one, a few, many particles

"analog"
full analog information
typically 14+ bits

F. Simon



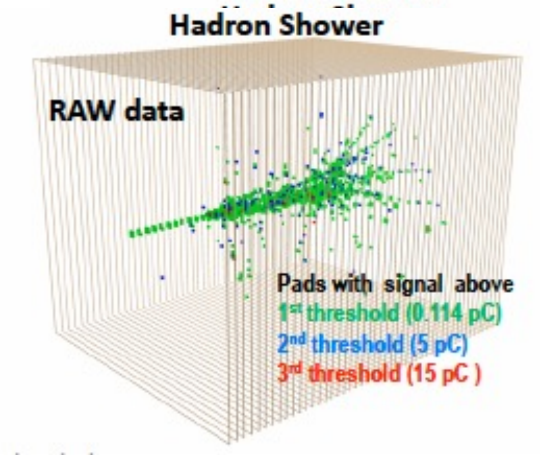
➔ 1x1 cm² pad: energy resolution in SDHCAL same as AHCAL with software compensation

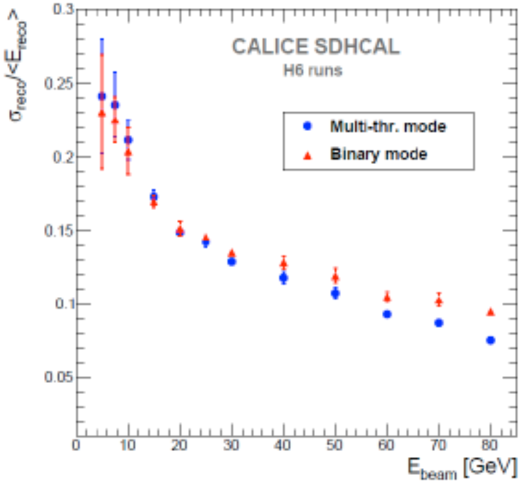
Studies done within CALICE collaboration:

- AHCAL Scint+SiPM 3 x 3 cm² granularity
- DHCAL glass RPC 1 x 1 cm² granularity
- SDHCAL RPC/MICROMEGAS/RPWELL 1 x 1 cm² granularity

New handle: Fast- timing

- If pico-second-time and energy informati at each point along the track
  - ⇒ 5D imaging reconstruction
- better assignment of deposit to PV timir
- Better construction of the shower





Slide © Anna Colaleo

Facilities: (ILC/C³, FCC-ee, CEPC, Muon collider, Hadron Physics).

Large Area Fast Timing Detectors

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m² achieved time res. ~ 60 ps)
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 μm-thick glass
  ➔ down to 20 ps time resolution

Z.Liu

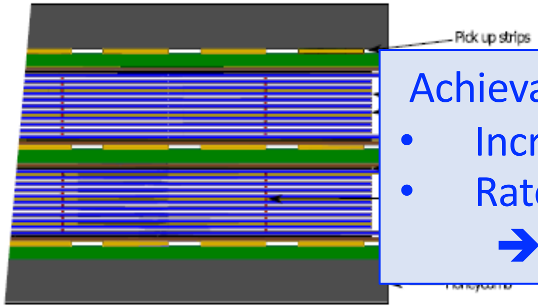
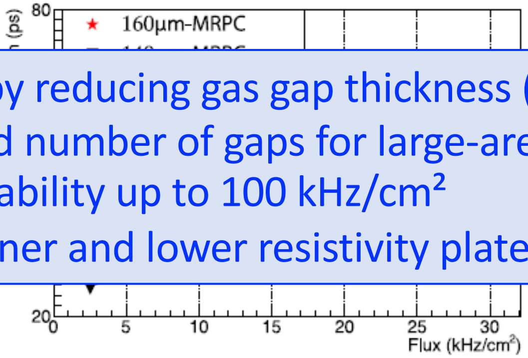
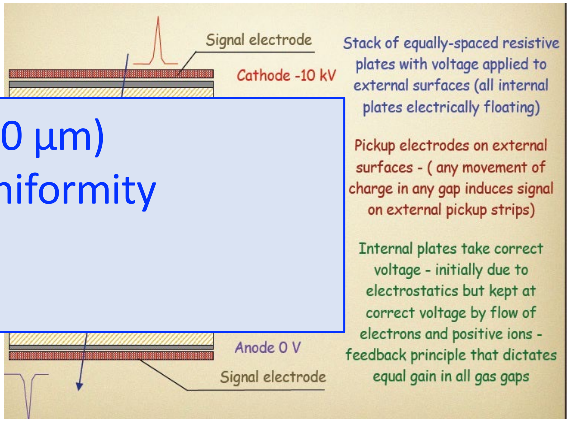


Fig. 1. Cross section of the double stack 20-gap MRPC.





Stack of equally-spaced resistive plates with voltage applied to external surfaces (all internal plates electrically floating)

Pickup electrodes on external surfaces - (any movement of charge in any gap induces signal on external pickup strips)

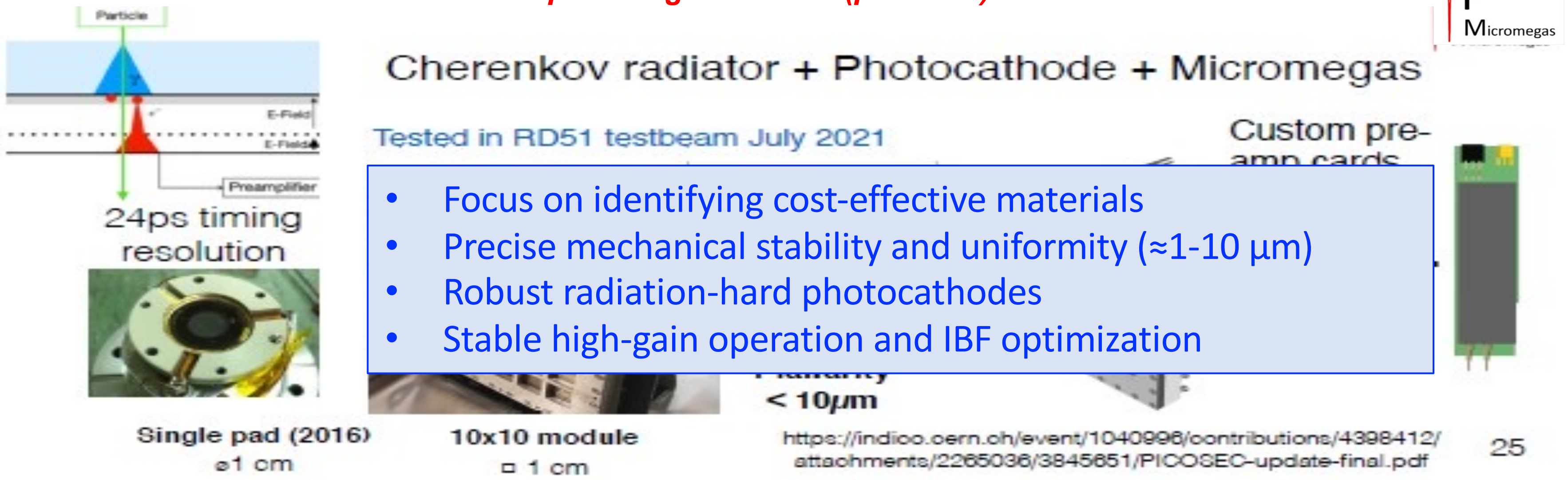
Internal plates take correct voltage - initially due to electrostatics but kept at correct voltage by flow of electrons and positive ions - feedback principle that dictates equal gain in all gas gaps

Achievable by reducing gas gap thickness (~100 μm)

- Increased number of gaps for large-area uniformity
- Rate capability up to 100 kHz/cm²
  ➔ Thinner and lower resistivity plates

Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

σ ~ 25 ps timing resolution (per track)



Cherenkov radiator + Photocathode + Micromegas

Tested in RD51 testbeam July 2021

Custom pre-amp cards

24ps timing resolution

Planarity < 10μm

Single pad (2016) ⌀1 cm

10x10 module □ 1 cm

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

25

- Focus on identifying cost-effective materials
- Precise mechanical stability and uniformity (≈1-10 μm)
- Robust radiation-hard photocathodes
- Stable high-gain operation and IBF optimization

Slide © Anna Colaleo

TPCs as reaction/decay chambers

TPCs are commonly used in rare event searches.
Lens-like Effect: Density-driven magnification/demagnification.

- **Different Readouts**: Charge, negative-ion, dual-phase, optical.
- Typically, MPGD are used for the TPC amplification stage.

WIMP, DM & Neutrino Experiments

Nuclear Recoil Discrimination:

  - **Large Tons @ high pressure** : Noble liquid (Ar, Xe) + gas (MPGD) amplification and readout.

Light element as target: low energy threshold and low radioactive background

  - **Ar o Ne mixture 1-10 bar with stable gain and without energy degradation**

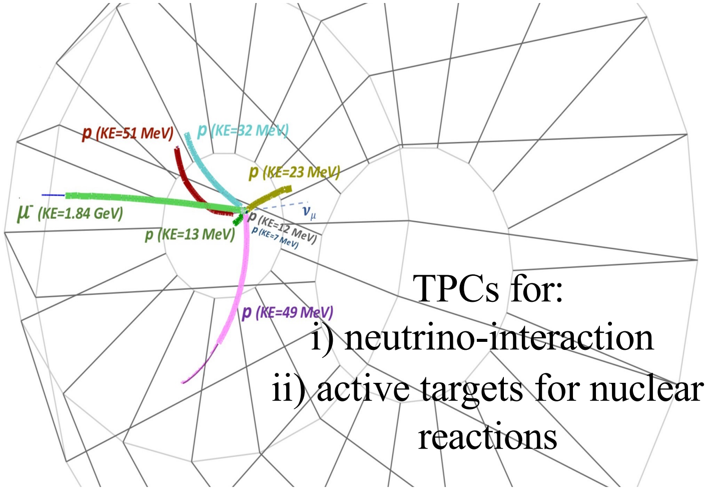
Direction of WIMP Flux

3D Reconstruction: 20 mbar - 1 bar pressure for accurate 3D tracking.

  - **Various Readout Methods**: Ionization electron, negative ions, electron ionization and optically based readouts at atmospheric pressure (Cygnus)

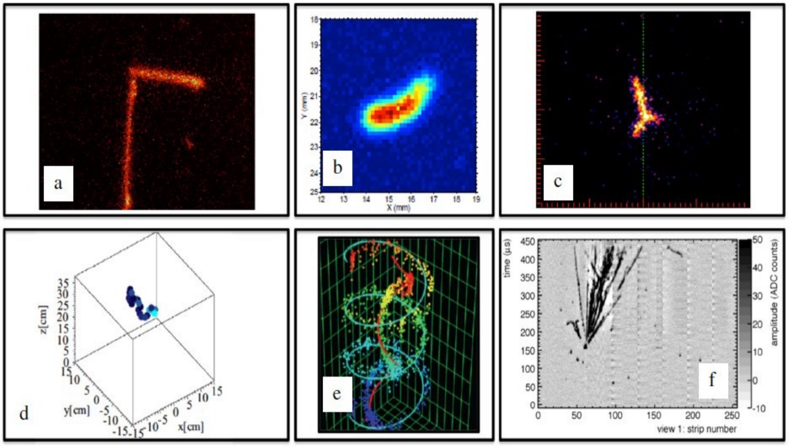
Particle Trackers for Neutrino Oscillation NDs

Pressurized Argon-based TPCs: E.g., Dune ND at 10 bar.



TPCs for:
i) neutrino-interaction
ii) active targets for nuclear reactions

‘TPC == single reconstruction-tool’



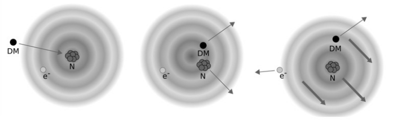
Future Perspectives on Gaseous Detectors

Some examples from the Migdal & Cygnus Experiments

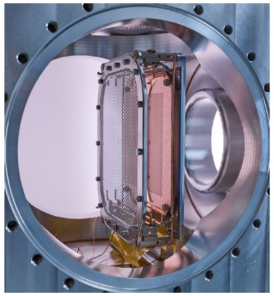
Invesigate Migdal effect (for DM-searches)
Cygnus Experiment for Directional DM-search

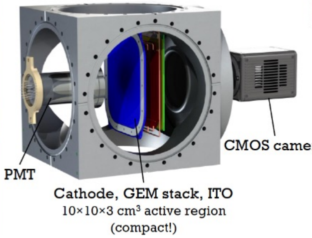
The MIGDAL optical-TPC

MIGDAL
Migdal In Galactic Dark mAtter expLoration



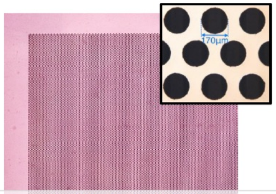
Migdal Effect - nucleus moves relative to the electron cloud. An individual electron might be left behind leading to ionisation.





Cathode, GEM stack, ITO
$10\times10\times3$ cm³ active region
(compact!)

Cathode woven mesh
280 μm Al wire



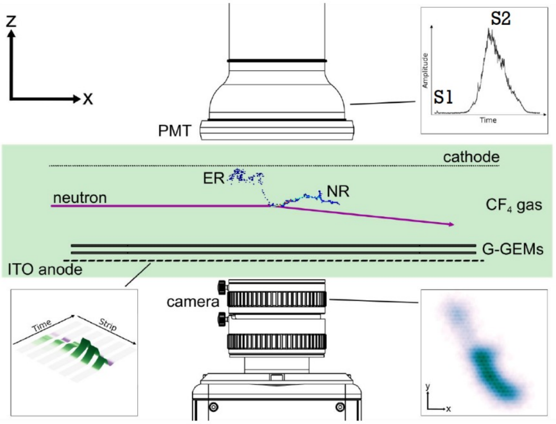
Double glass-GEMs
Diameter: 170 μm | pitch: 280 μm | thickness: 570 μm

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Triple readout

- Amplification: 2x glass-GEMs
- Optical: camera + photomultiplier tube
- Charge: 120 ITO anode strips

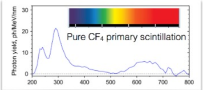
Charge readout | Optical readout



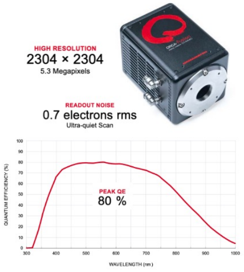
LIME: LARGE IMAGING MODULE

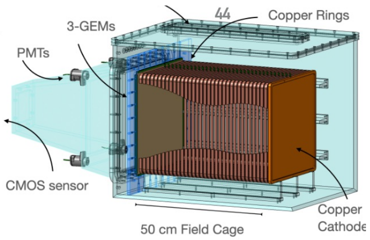
33 x 33 ~ 1000 cm² GEM surface;
50 cm drift path;

50 litres sensitive volume with an **He/CF₄** based mixture at **atmospheric pressure**

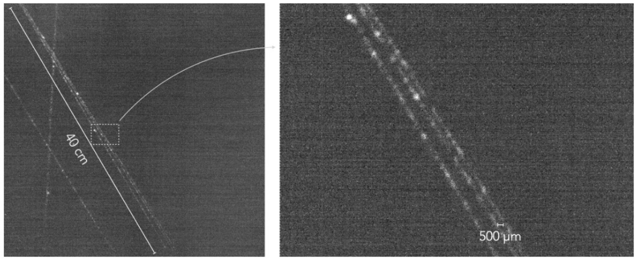


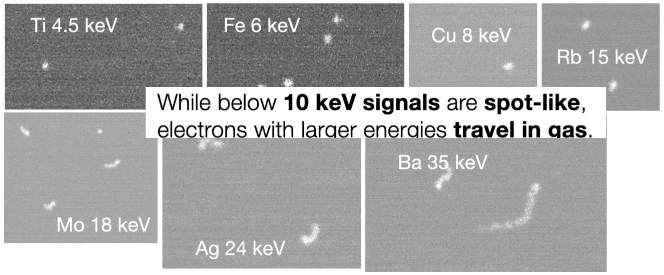
ORCA-Fusion



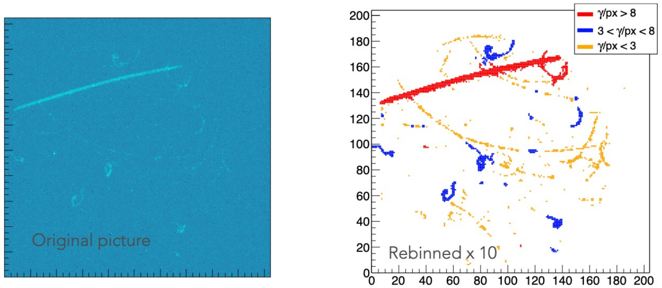


Example of a few cosmic tracks in LIME (Long Imaging ModulE)





While below **10 keV signals** are **spot-like**, electrons with larger energies **travel in gas**.



By simply assigning **different colours** to identify clusters as a function of their **average light density**, the three species are almost completely separated.

Slide Materials © Davide Pinci

Future Perspectives on Gaseous Detectors

6. Implementation of the Detector R&D (DRD1) collaboration

R&D FRAMEWORK

- **Collaboration type: Community-driven** with the **R&D environment:** common infrastructures (labs, workshops), common R&D tools (software and electronics), cross-disciplinary exchange

- **Scientific organization in Working Groups:** provides a platform for sharing knowledge, expertise, and efforts, by playing a crucial role in identifying, guiding, and supporting strategic detector R&D directions, facilitating the establishment of joint projects between institutes.

R&D PROJECTS

- **Work Packages (WP):** long-term project addressing strategic R&D goals, **outlined in the updated European Strategy for Particle Physics** with dedicated funding lines.

- **Common Projects (CP):** short-term blue-sky R&D or common tool development with limited time and resources, supported by the Collaboration Common funds.

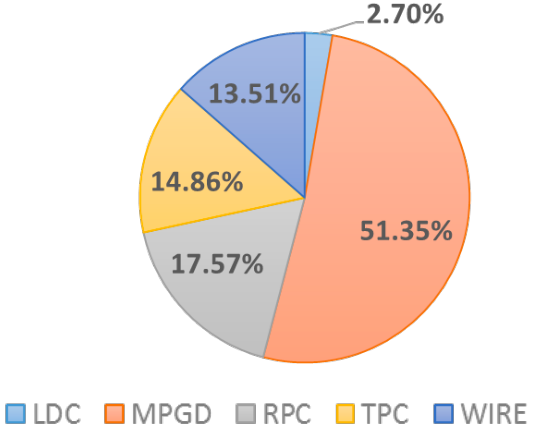
DRDT *

1.1	1.2	1.3	1.4	WG2 Applications
●		●		Trackers/Hodoscopes (large area muon systems, inner tracking/vertexing)
●	●	●		Inner and central tracking with PID capability
●		●		Calorimetry
●	●	●		Photo-detectors (PID)
●	●	●		Timing detectors (PID and trigger)
			●	TPCs as reaction and decay chambers (rare events, neutrino physics, nuclear physics)

Tools and infrastructures

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

Technology interests in DRD1
(based on initial Survey)

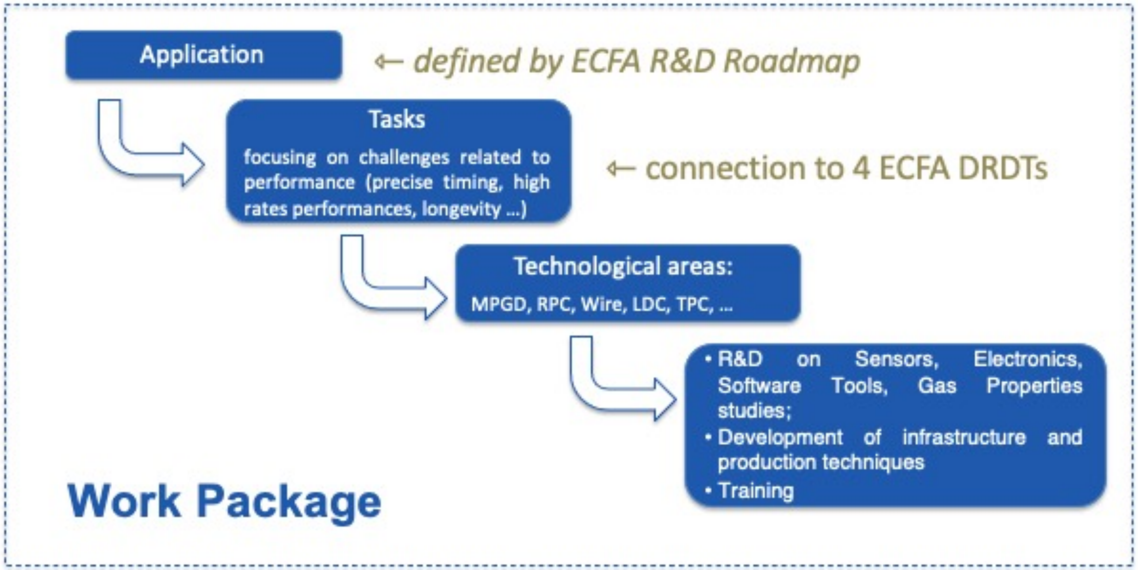


Slide © Anna Colaleo

Implementation of DRD1 Collaboration

Strategic R&D => Work Packages

- **Group together institutes research interests** around **Applications** with a focus on a **specific task(s)** devoted to a specific challenge (Detector R&D theme*), typically related to specific **Detector Technologies** and to the development of **specific tool or infrastructure**



Application ← *defined by ECFA R&D Roadmap*

Tasks

focusing on challenges related to performance (precise timing, high rates performances, longevity ...) ← connection to 4 ECFA DRDTs

Technological areas:

MPGD, RPC, Wire, LDC, TPC, ...

- R&D on Sensors, Electronics, Software Tools, Gas Properties studies;
- Development of infrastructure and production techniques
- Training

Work Package

Currently implemented WPs

- WP1: trackers/hodoscopes
- WP2: Drift Chambers
- WP3: Straw Chambers
- WP4: Tracking TPCs
- WP5: Calorimetry
- WP6: Photon detectors
- WP7: Timing detectors
- WP8: Reaction/Decay TPCs

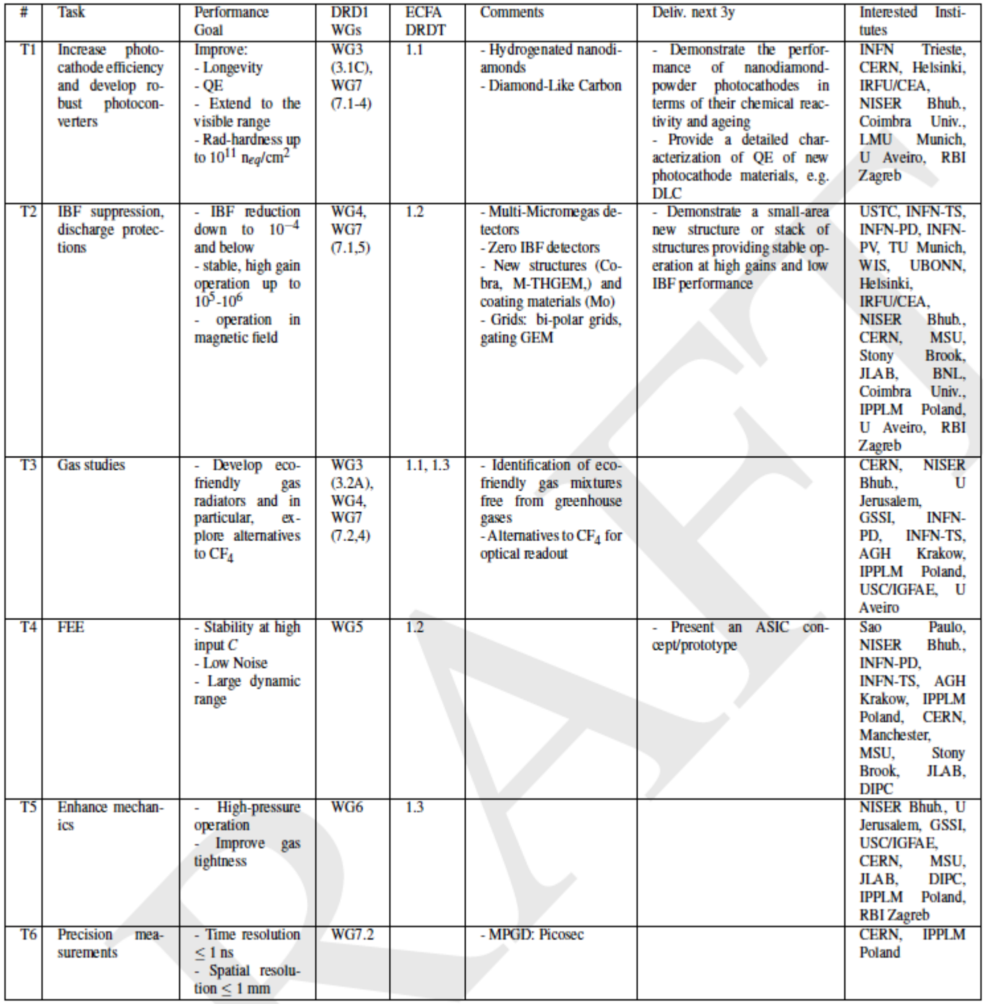
Additional WP on beyond fundamental physics also considered

Slide © Anna Colaleo

DRD1 Work Package

Example for Photon Detectors (WP6)

NEW Slide



#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Increase photocathode efficiency and develop robust photoconverters	Improve: - Longevity - QE - Extend to the visible range - Rad-hardness up to 10^{11} n_{eq}/cm^2	WG3 (3.1C), WG7 (7.1-4)	1.1	- Hydrogenated nanodiamonds - Diamond-Like Carbon	- Demonstrate the performance of nanodiamond-powder photocathodes in terms of their chemical reactivity and ageing - Provide a detailed characterization of QE of new photocathode materials, e.g. DLC	INFN Trieste, CERN, Helsinki, IRFU/CEA, NISER Bhub., Coimbra Univ., LMU Munich, U Aveiro, RBI Zagreb
T2	IBF suppression, discharge protections	- IBF reduction down to 10^{-4} and below - stable, high gain operation up to 10^5-10^6 - operation in magnetic field	WG4, WG7 (7.1,5)	1.2	- Multi-Micromegas detectors - Zero IBF detectors - New structures (Cobra, M-THGEM,) and coating materials (Mo) - Grids: bi-polar grids, gating GEM	- Demonstrate a small-area new structure or stack of structures providing stable operation at high gains and low IBF performance	USTC, INFN-TS, INFN-PD, INFN-PV, TU Munich, WIS, UBONN, Helsinki, IRFU/CEA, NISER Bhub., CERN, MSU, Stony Brook, JLAB, BNL, Coimbra Univ., IPPLM Poland, U Aveiro, RBI Zagreb
T3	Gas studies	- Develop eco-friendly gas radiators and in particular, explore alternatives to CF_4	WG3 (3.2A), WG4, WG7 (7.2,4)	1.1, 1.3	- Identification of eco-friendly gas mixtures free from greenhouse gases - Alternatives to CF_4 for optical readout		CERN, NISER Bhub., U Jerusalem, GSSI, INFN-PD, INFN-TS, AGH Krakow, IPPLM Poland, USC/IGFAE, U Aveiro
T4	FEE	- Stability at high input C - Low Noise - Large dynamic range	WG5	1.2		- Present an ASIC concept/prototype	Sao Paulo, NISER Bhub., INFN-PD, INFN-TS, AGH Krakow, IPPLM Poland, CERN, Manchester, MSU, Stony Brook, JLAB, DIPC
T5	Enhance mechanics	- High-pressure operation - Improve gas tightness	WG6	1.3			NISER Bhub., U Jerusalem, GSSI, USC/IGFAE, CERN, MSU, JLAB, DIPC, IPPLM Poland, RBI Zagreb
T6	Precision measurements	- Time resolution ≤ 1 ns - Spatial resolution ≤ 1 mm	WG7.2		- MPGD: Picosec		CERN, IPPLM Poland

Challenges for the photon detectors

Preserving Photocathode Efficiency:

1. Suppressing ion backflow
2. Developing more robust photoconverters

1.Front-End Electronics (FEE):

1. Development of very low noise FEE
2. Large dynamic range FEE

2.Detector Performance Improvement:

1. Enhanced spatial resolution
2. Improved time resolution
3. Fast charge collection for maximum rate capability

3.TRD System Enhancement:

1. Better separation between transition radiation and ionization process in TRD systems

Area of application: nuclear physics, hadron physics, future ee, and eA machines. Timeline: >2030

Slide © Anna Colaleo

WPs are currently in preparation: interested institutes are drafting confidential documents with detailed information about milestones, deliverables over the years and available/needed resources for the R&D program accomplishment.

Implementation of DRD1 Collaboration

Common Tools & Infrastructure => Working Groups

e.g. Working Group 3
Gas & Material studies

Topics covered by the WG3: gas and material studies

Address common key issues related to gas and materials
in the development of existing and future gaseous detectors

Gas
- Gas Properties (e.g. cross-section, chemical characterization, measurements)
- Eco-gases studies
- Light emission in gas

Systems
- Gas recuperation and recirculation systems
- Gas systems
- Sealed detectors and systems

Materials
- Resistive electrodes
- Solid converters
- Photocathodes (novel, aging, protection)
- Novel materials (e.g. nanomaterials)
- Material properties for detector and infrastructure
- Light (low material budget) materials
- Precise mechanics

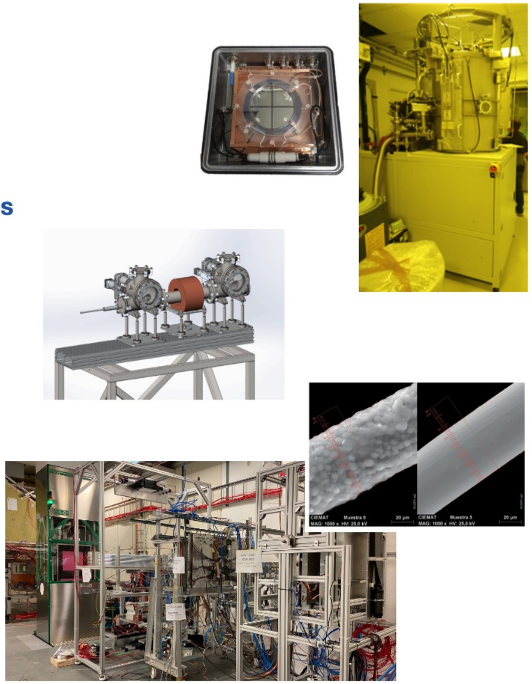
Long-term operation
- Ageing
- Outgassing
- Radiation hardness

Synergies and common aspects between technologies

Resistive material
- Common topic for MPGD and RPC
- Common development of new materials
- Use of same tools/facilities to construct/test materials

Precise mechanics and material properties
- Common topic for all technologies
- Mechanical tests
- Outgassing tests
- Radiation hardness

Ageing studies
- Common topic for all technologies
- Experience in common
- Material studies
- Radiation hardness studies
- Analysis: gas and material



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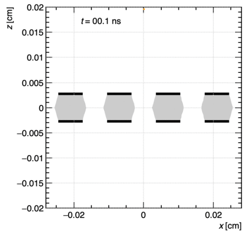
Implementation of DRD1 Collaboration

Common Tools & Infrastructure => Working Groups

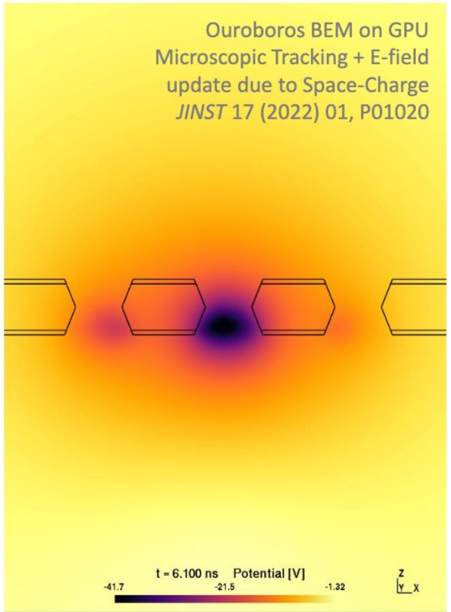
e.g. Working Group 4
Simulation, Modelling & SW

- **WG4 Aims at:**
  - Understanding & modelling Physical Processes in Gaseous Det (GD)
  - *Development of Suitable Simulation & Software Tools*
- **Importance within DRD1:**
  - Advanced simulations indispensable for GD Detector R&D
  - *Confirm* / *Challenge* current understanding of Detector Physics
  - *Note:* SW Tools developed within GD community now used for other detection technologies (Liquid / Solid State)

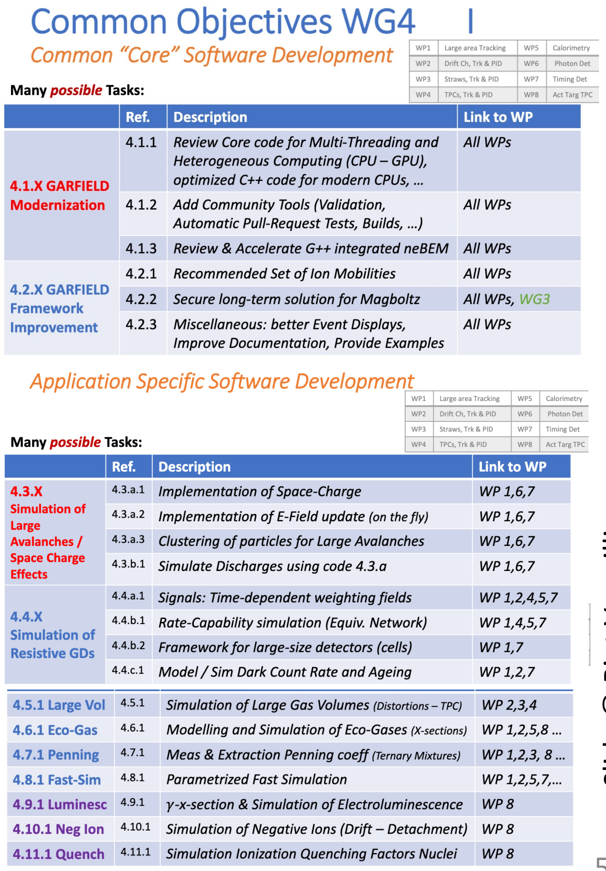


Main Limitations of the current simulation Tools

- Long computing times / Prohibitive resource use of precise and realistic simulations
  - Large Gains, Large Rates
  - Space-Charge effects (see also GEMs)
- Non-correct signal shape simulation
  - Need correct ion species & ion mobilities
- Dynamic behaviour (Rate => V-drop)
- Unknown effects
  - Discharge transition
  - Ageing effects
- New / Innovative Gases
  - Simulation is ideal tool to survey multi-dimensional Parameter space – but need cross-sections of candidate gas components
- New concepts:
  - Neg Ion drift & amplification
  - Electroluminescence & optical readout



Ouroboros BEM on GPU
Microscopic Tracking + E-field update due to Space-Charge
JINST 17 (2022) 01, P01020



Common Objectives WG4 I

Common "Core" Software Development

WP1	Large area Tracking	WP5	Calorimetry
WP2	Drift Ch, Trk & PID	WP6	Photon Det
WP3	Straws, Trk & PID	WP7	Timing Det
WP4	TPCs, Trk & PID	WP8	Act Targ TPC

Many *possible* Tasks:

	Ref.	Description	Link to WP
4.1.X GARFIELD Modernization	4.1.1	*Review Core code for Multi-Threading and Heterogeneous Computing (CPU – GPU), optimized C++ code for modern CPUs, …*	*All WPs*
	4.1.2	*Add Community Tools (Validation, Automatic Pull-Request Tests, Builds, …)*	*All WPs*
	4.1.3	*Review & Accelerate G++ integrated neBEM*	*All WPs*
4.2.X GARFIELD Framework Improvement	4.2.1	*Recommended Set of Ion Mobilities*	*All WPs*
	4.2.2	*Secure long-term solution for Magboltz*	*All WPs, WG3*
	4.2.3	*Miscellaneous: better Event Displays, Improve Documentation, Provide Examples*	*All WPs*

Application Specific Software Development

WP1	Large area Tracking	WP5	Calorimetry
WP2	Drift Ch, Trk & PID	WP6	Photon Det
WP3	Straws, Trk & PID	WP7	Timing Det
WP4	TPCs, Trk & PID	WP8	Act Targ TPC

Many *possible* Tasks:

	Ref.	Description	Link to WP
4.3.X Simulation of Large Avalanches / Space Charge Effects	4.3.a.1	*Implementation of Space-Charge*	*WP 1,6,7*
	4.3.a.2	*Implementation of E-Field update (on the fly)*	*WP 1,6,7*
	4.3.a.3	*Clustering of particles for Large Avalanches*	*WP 1,6,7*
	4.3.b.1	*Simulate Discharges using code 4.3.a*	*WP 1,6,7*
4.4.X Simulation of Resistive GDs	4.4.a.1	*Signals: Time-dependent weighting fields*	*WP 1,2,4,5,7*
	4.4.b.1	*Rate-Capability simulation (Equiv. Network)*	*WP 1,4,5,7*
	4.4.b.2	*Framework for large-size detectors (cells)*	*WP 1,7*
	4.4.c.1	*Model / Sim Dark Count Rate and Ageing*	*WP 1,2,7*
4.5.1 Large Vol	4.5.1	*Simulation of Large Gas Volumes (Distortions – TPC)*	*WP 2,3,4*
4.6.1 Eco-Gas	4.6.1	*Modelling and Simulation of Eco-Gases (X-sections)*	*WP 1,2,5,8 …*
4.7.1 Penning	4.7.1	*Meas & Extraction Penning coeff (Ternary Mixtures)*	*WP 1,2,3, 8 …*
4.8.1 Fast-Sim	4.8.1	*Parametrized Fast Simulation*	*WP 1,2,5,7,…*
4.9.1 Luminesc	4.9.1	*γ-x-section & Simulation of Electroluminescence*	*WP 8*
4.10.1 Neg Ion	4.10.1	*Simulation of Negative Ions (Drift – Detachment)*	*WP 8*
4.11.1 Quench	4.11.1	*Simulation Ionization Quenching Factors Nuclei*	*WP 8*

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Implementation of DRD1 Collaboration

Common Tools & Infrastructure => Working Groups

e.g. Working Group 7
Common Test Infrastructure

COMMON TEST BEAM

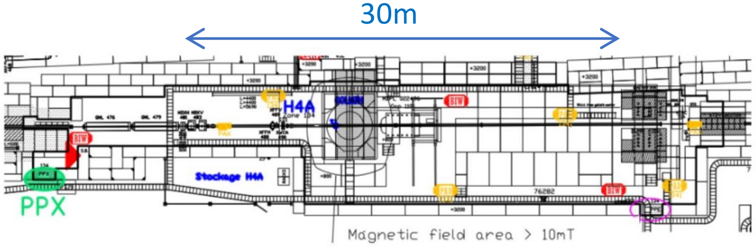
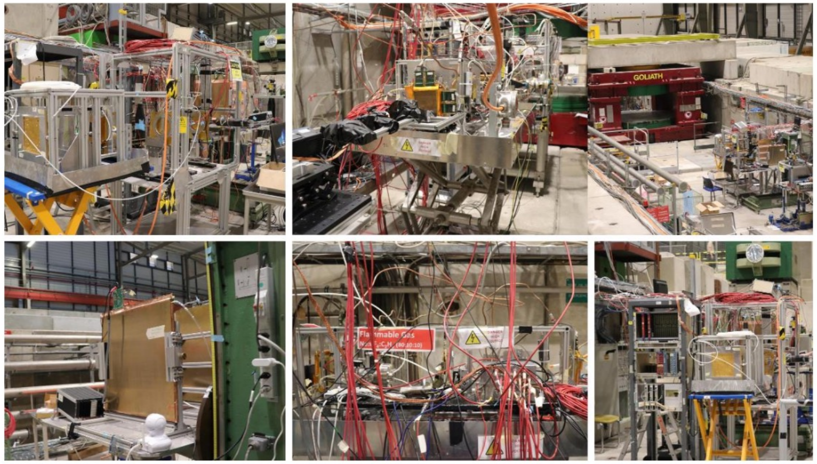


Fig.2: CERN North Area SPS Extraction line, H4 Beam line (PPE134/EHN1)



30 m	3-4 x year	≤ 360 GeV/c
10^7 particles/spill ~1 spill/minute	π, μ, e, p	$\frac{\Delta p}{p} \leq 1.5\%$

IRRADIATION FACILITIES

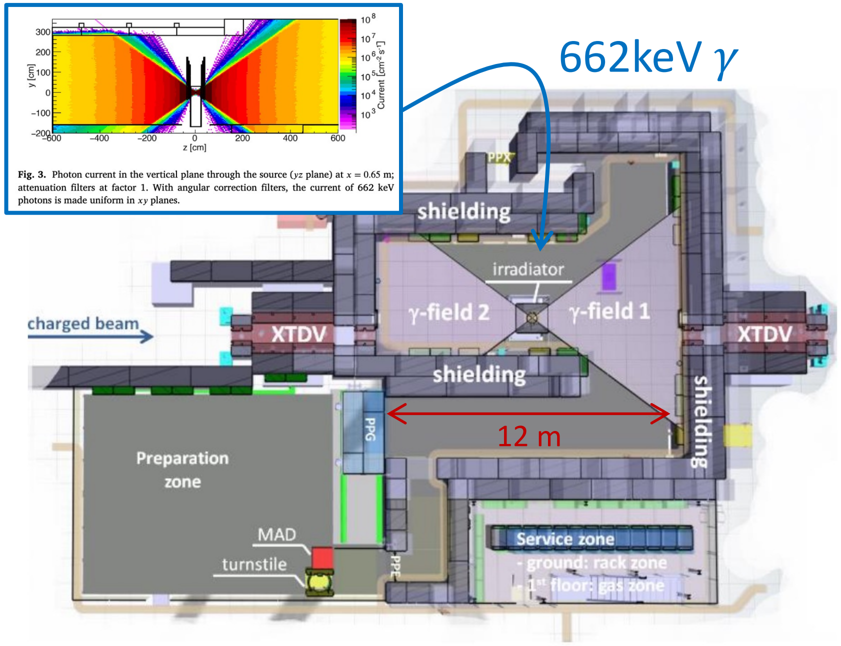


Fig. 3. Photon current in the vertical plane through the source (*yz* plane) at $x = 0.65$ m; attenuation filters at factor 1. With angular correction filters, the current of 662 keV photons is made uniform in *xy* planes.

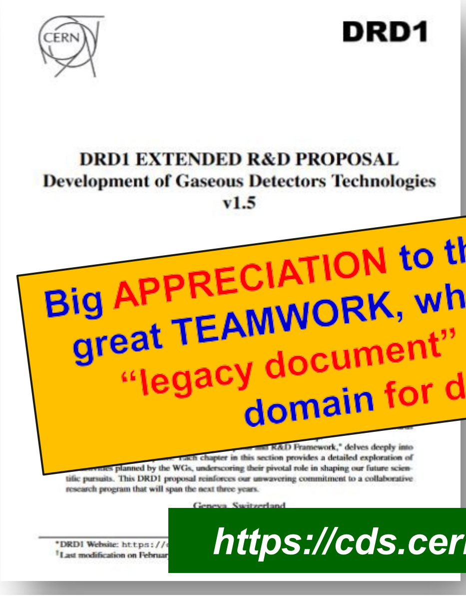
First step: GIF++
understand access modality and needs in the community

12 m	137 Cs	14 TBq

Slide © Y.Tsipolitos & E.Oliveri

DRD1 Collaboration in Action 2024 - …

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



DRD1

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

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

Geneva, Switzerland

*DRD1 Website: https://…
†Last modification on Februar…

I.7 DRD1 Implementation Team

I.7.1 Roles covered during the DRD1 Implementation Phase

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

Task Force Conveners
Anna Colaleo, Leszek Ropelewski;

Implementation Team Florian Brunbauer , Silvia Dalla Torre , Klaus Dehmelt , Ingo Deppner , Esther Ferrer Ribas , Roberto Guida , Giuseppe Iaselli , Jochen Kaminski , Barbara Liberti , Beatrice Mandelli , Eraldo Oliveri , Marco Panareo , Francesco Renga , H…s Taureg , Fulvio Tessarotto , Maxim Titov , Joao Veloso , Peter W…

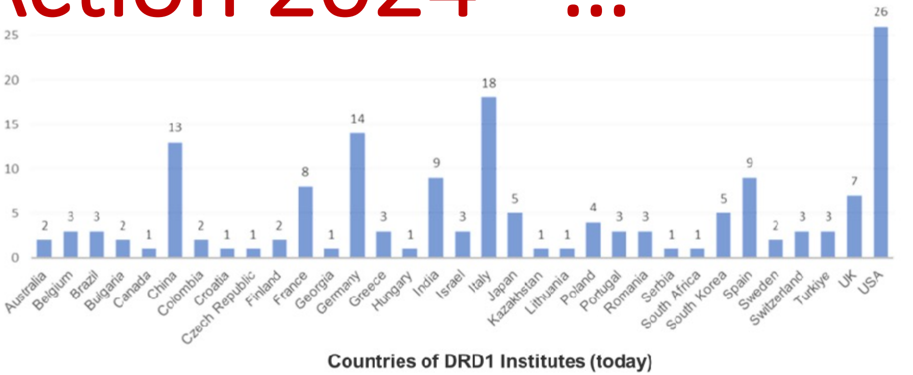
Proposal Review T…

…I. Laktineh
…, T. Tsipolitis
…Brunbauer, M. Iodice, B. Liberti, A Paoloni

Work Package Coordinators
Overall Coordination: P. Gasik
WP1: G. Aielli, R. Farinelli, M. Iodice, A. Ochi, G. Pugliese
WP2: N. De Filippis, F. Grancagnolo
WP3: P. Wintz
WP4: D. Gonzalez Diaz, E. Ferrer Ribas, F. I. Garcia Fuentes, P. Gasik, J. Kaminski
WP5: I. Laktineh

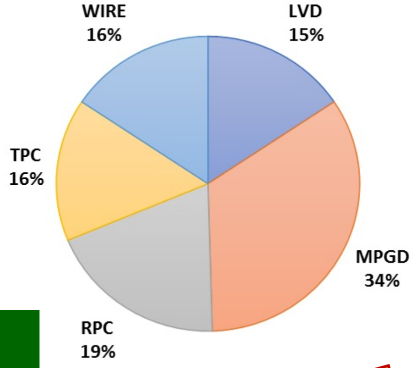
Big APPRECIATION to the DRD1 COMMUNITY for great TEAMWORK, which allowed to shape the "legacy document" for gaseous detectors domain for decades to come

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



Countries of DRD1 Institutes (today)

https://drd1.web.cern.ch



February 2025

27 Feb - 28 Feb DRD1 Topical Workshop on Detector Manufacturing and Production (Preliminary Agenda)

24 Feb - 28 Feb 4th DRD1 Collaboration Meeting and Topical Workshop on Detector Manufacturing and Production (Preliminary Agenda)

December 2024

09 Dec - 13 Dec 3rd DRD1 Collaboration Meeting

June 2024

17 Jun - 21 Jun 2nd DRD1 Collabora… Gaseous Detectors

January 2024

29 Jan - 02 Feb 1st DRD1 Collaboration…

June 2023

22 Jun - 23 Jun DRD1 Community Meeting

March 2023

01 Mar - 03 Mar DRD1 Community Meeting

2023: 2 community meetings
2024: 3 collaboration meetings,
Several WG meetings, WP meetings, CB meetings, …

DRD1
Gaseous Detectors
School

CERN
November 27 - December 6, 2024

Scientific program

- Gaseous detector physics
- Gaseous detector technologies
- Readout technologies
- Simulation, modelling and reconstruction
- Manufacturing techniques
- Applications of gaseous detectors

The school consists of academic lectures and hands-on laboratory exercises.

The lecture program will cover MPGD, (M)RPC and wire-based detector technologies.

Lecture sessions are open to the community and can be followed in-person or by remote connection.

School website and registration

https://indico.cern.ch/e/drd1school2024

Application deadline: July 31, 2024

Free registration for students.

Students are invited to present a poster in a dedicated session.

Contact: drd1-school@cern.ch

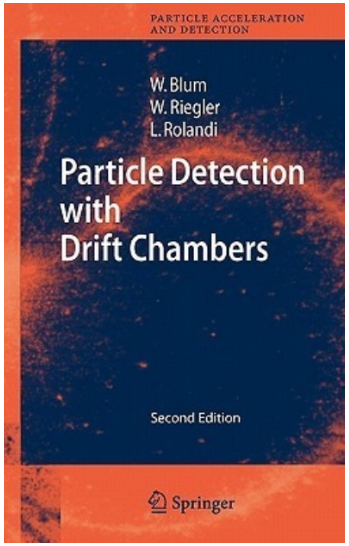
First School for PhD Students

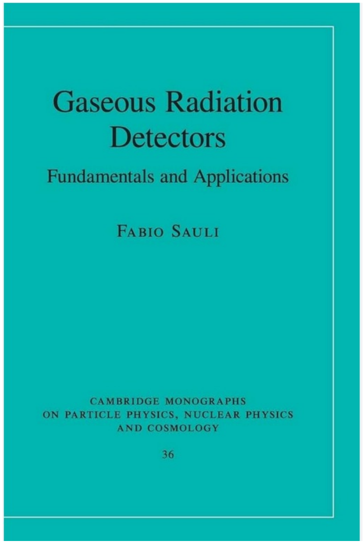
Conclusions, final Thoughts, … and Questions

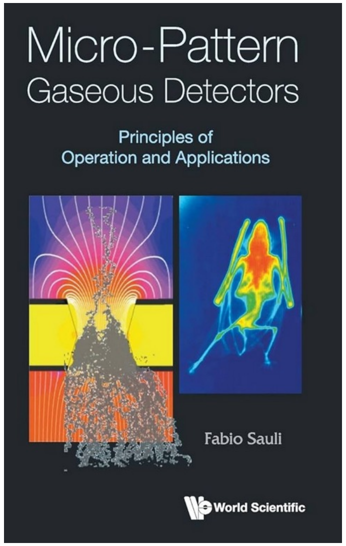
- **Physics discoveries are mostly Tool-Driven**
- Gaseous detectors are around for > 100 years
  - *They have undergone many improvements / revolutions*
  - *Are relatively "easy" to build and to modify*
  - Simulation tools have been developed in the past
    - *Are freely available to you to play around with*
    - *However are not complete and require you to develop further*
    - *Remember: with Simulation you prove you understand your Results*
- **Understanding State-of-the-Art detectors allows you to propose modifications to improve them further**
- **The DRD1 collaboration groups GD experts worldwide**
  - To share new developments, to develop new tools, to test together
  - To work together on the development of Detectors of the future
  - To create a friendly atmosphere where one can learn and teach
  - We are waiting for you to join and push the limits of instrumentation

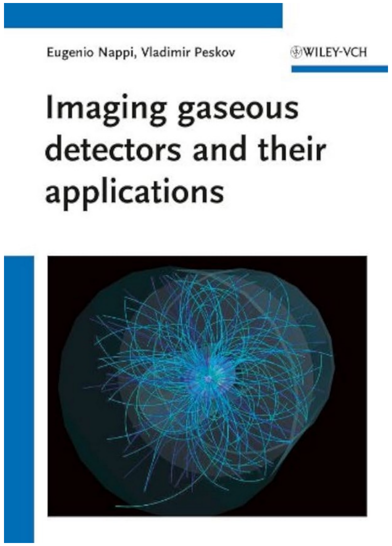
Acknowledgements & References

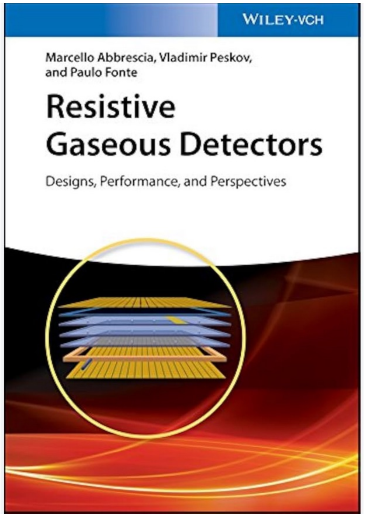
- “*If I have seen further it is by standing on the shoulders of GIANTS*” – Isaac Newton
  - *I have not seen further, but I still thank all GIANTS that have introduced me to the field and of who I have recycled slides, materials, ideas ….*
- Recommended REFERENCE books:











- Recommended LECTURE series:
  - **Werner Riegler – Signals in Detectors - 2019 - https://indico.cern.ch/event/843083/**
  - **Rob Veenhof – MPGDs - 2017 - https://indico.cern.ch/event/676702**

Acknowledgements & References

- Interesting SEMINARS:
  - CERN Detector Seminar series: https://indico.cern.ch/category/84/
- A non-exhaustive selection:
  - S.Levorato – Technical Challenges for the new T2K high-angle TPCs https://indico.cern.ch/event/1431318/
  - M.Bianco – The GEM Detectors within the CMS Experiment https://indico.cern.ch/event/1175363/
  - E. Oliveri – Charged particle timing in the sub-50ps regime with Micromegas https://indico.cern.ch/event/667607/
  - F. Sauli – GEM Detectors 20 years of Development and Applications https://indico.cern.ch/event/574840/
  - E. Nappi – Trends and Perspectives of RICH detectors in High Energy Physics https://indico.cern.ch/event/178123/
  - C. Garabatos – The ALICE TPC Upgrade with GEMs https://indico.cern.ch/event/275624/
  - C. Williams – ALICE Time of Flight Detectors https://indico.cern.ch/event/149006/
  - S.Dalla Torre – Novel Photon Detectors based on Thick GEM technology for COMPASS https://indico.cern.ch/event/145264/
- DRD1 Gaseous Detector School: https://indico.cern.ch/category/18473/

Future Perspectives on Gaseous Detectors

and DRD1 R&D Program

Back-up slides

Picture © Luigi Filici CCBY License

ECFA Detector R&D Roadmap content

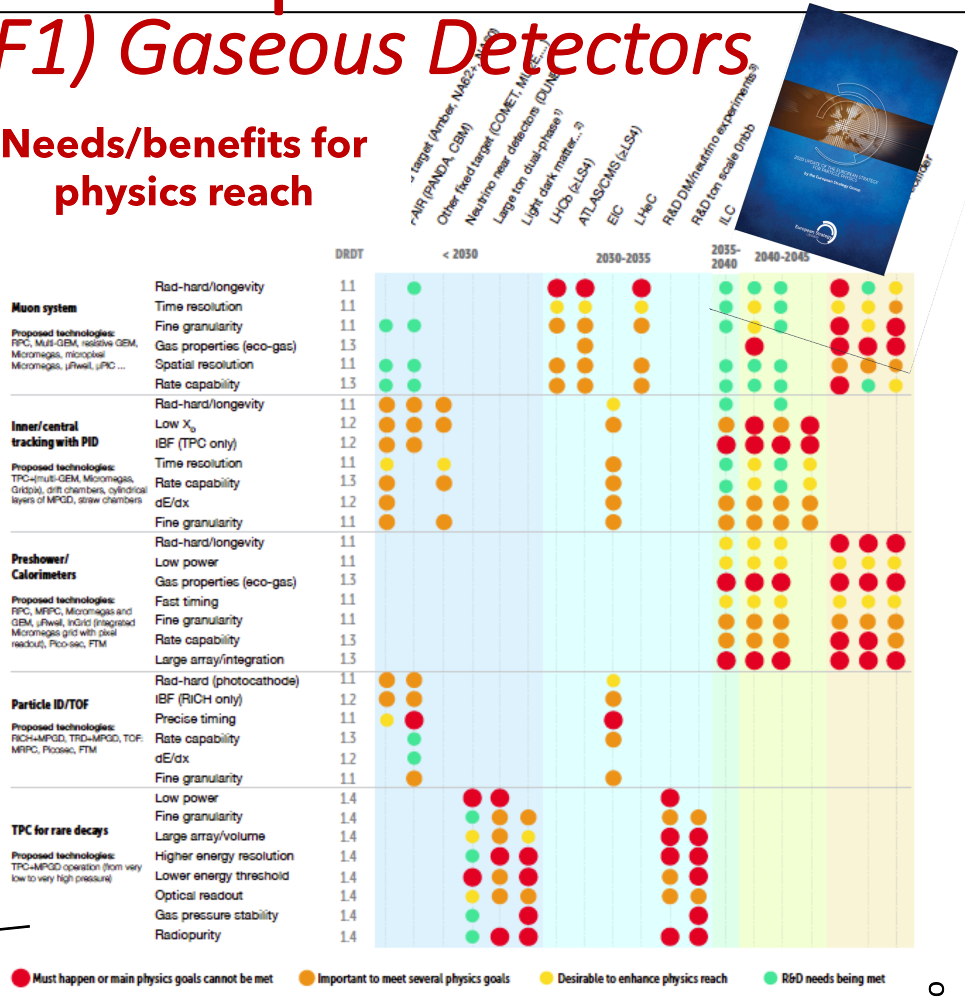
Example for Task Force 1 (TF1) Gaseous Detectors

Performance targets and main drivers from facilities

Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm² Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm² (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA)**: Max. rate: 10 kHz/cm² Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm²
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm² ($\theta<8^0$) < 2 kHz/cm² (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm²
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR)**: Max rate: <500 kHz/cm² Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{13} neq/cm²/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm² Spatial resolution = 50 μm Angular resolution = 70 μrad (η=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

Ex. Muon system

Needs/benefits for physics reach



		DRDT
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1
	Time resolution	1.1
	Fine granularity	1.1
	Gas properties (eco-gas)	1.3
	Spatial resolution	1.1
	Rate capability	1.3
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1
	Low X_0	1.2
	IBF (TPC only)	1.2
	Time resolution	1.1
	Rate capability	1.3
	dE/dx	1.2
	Fine granularity	1.1
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1
	Low power	1.1
	Gas properties (eco-gas)	1.3
	Fast timing	1.1
	Fine granularity	1.1
	Rate capability	1.3
	Large array/integration	1.3
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1
	IBF (RICH only)	1.2
	Precise timing	1.1
	Rate capability	1.3
	dE/dx	1.2
	Fine granularity	1.1
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4
	Fine granularity	1.4
	Large array/volume	1.4
	Higher energy resolution	1.4
	Lower energy threshold	1.4
	Optical readout	1.4
	Gas pressure stability	1.4
	Radiopurity	1.4

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Detector R&D Themes (DRDTs)

DRDT 1.1 - Improve time and spatial resolution for gaseous detectors with longterm stability

DRDT 1.2 - Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes

DRDT 1.3 - Develop environmentally friendly gaseous detectors for very large areas with high-rate capability

DRTD 1.4 - Achieve high sensitivity in both low and high-pressure TPCs

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ECFA Detector R&D Roadmap

Summary of R&D Challenges for different Applications

Muon System	Inner and Central tracking	Calorimetry	Photon detection	TOF	Rare decays
● Radiation hardness and stability of large area up to integrated charges of hundreds of C/cm2: - aging issues and discharges; ● Operation in a stable and efficient manner with incident particle flows up to ~10 MHz/cm2: - miniaturization of readout elements needed to keep occupancy low; ● Manufacturing, on an industrial scale, large detectors at low cost, by means of a process of technological transfer to the industry and identifies processes transferable to industries ● Identification of eco-friendly gas mixture and mitigation of the issue related to the operation with high WGP gas mixture: - gas tightness;gas recuperation system;accessibility for repairing. ● Study of resistive materials (RPC and MPGD): - higher gain in a single multiplication layer, with a remarkable advantage for assembly, mass production and cost. - new material and production techniques for resistive layers for increasing the rate capability ● Thinner layers and mechanical precision over large area	**Drift chambers** ● High rate, unique volume, high granularity, low mass ● Hydrocarbon-free mixture for long-term and high-rate operation ● Prove the cluster counting principle with the related electronics ● Mechanics: new wiring procedure, new wire materials ● Integration: accessibility for repairing. **TPC** ● R&D on detector sensors to suppress the IBF ratio ● Optimize IBF together with energy resolution ● Gain optimization: IBF, discharge stability ● Uniformity of the response of the sensors ● Gas mixture: stability, drift velocity, ion mobility, aging ● Influence of Magnetic field on IBF) ● High spatial resolution ● Very low material budget (few %) ● Mechanics: thickness minimization but robust for precise electrical properties for stable drift velocity. ● Integration: cooling of electronics. **Straw chambers** ● Ultra-long and thin film tubes; ● “Smart“ designs: self-stabilized straw module, compensating relaxation; ● Small diameter for faster timing, less occupancy, high rate capability; ● Reduced drift time, hit leading times and trailing time resolutions, with dedicated R&D on the electronics; ● PID by dE/dx with “standard“ time readout and time-over-threshold; ● 4D-measurement: 3D-space and (offline) track time; ● Over-pressurized tubes in vacuum: control the leakage rate to maintain the shape.	● Uniformity of the response of the large area and dynamic energy range; ● Optimization of weights for different thresholds in digital calorimeters ● Rate capability in detectors based on resistive materials: resistivity uniformity, discharge issue at high rate and in large area detector; ● R&D on sub-ns in active elements: resolution stables over wide range of fluxes; ● Gas homogeneity and stable over time. ● Eco-friendly gas mixture for RPC; ● Stability of the gas gain: fast monitoring of gas mixture and environmental conditions; ● Mechanics: - large area needed to avoid dead zone: limitation on size and planarity of PCB is an issue. - multi-gap with ultra-thin modules: very thin layer of glass and HPL electrodes, gas gap thickness uniformity few micron	● Preserve the photocathode efficiency by IBF and more robust photoconverters; ● Gas radiator: alternative to CF4 ● Gas tightness ● Very low noise when coupling large capacitance; ● Large dynamic range of the FEE; ● Separate the TR radiation and the ionization process ● InTDD use of cluster counting technique and improve it by means of a Ingrid.	● Uniform rate capability and time resolution over large detector area; ● New material for high rate (low resistivity, radiation hardness); - uniform gas distribution; - thinner structures: mechanical stability and uniformity; ● Eco-gas mixture; ● Electronics: Low noise, fast rise time, sensitive to small charge; ● Possibly optical readout; ● Precise clock distribution and synchronization over large area.	● Radio-purity of the materials ● Low background ● High granularity ● For large volume detectors: transparency over large distance ● Pressure stability and control ● Electronics with large dynamic range and flexible configuration. ● Self-trigger capability ● Low noise electronics ● Fast electronics ● Optical readout

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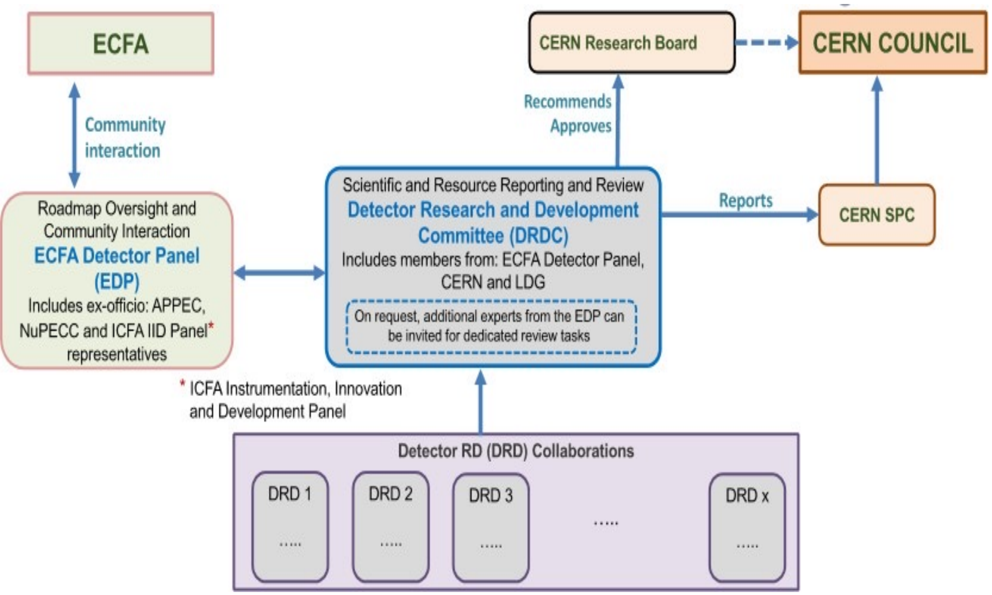
DRD1 Approval Process & Review



ECFA

Community interaction

CERN Research Board

CERN COUNCIL

Recommends
Approves

Scientific and Resource Reporting and Review
Detector Research and Development Committee (DRDC)
Includes members from: ECFA Detector Panel, CERN and LDG

On request, additional experts from the EDP can be invited for dedicated review tasks

Reports

CERN SPC

Roadmap Oversight and Community Interaction
ECFA Detector Panel (EDP)
Includes ex-officio: APPEC, NuPECC and ICFA IID Panel* representatives

* ICFA Instrumentation, Innovation and Development Panel

Detector RD (DRD) Collaborations

DRD 1 ….. | DRD 2 ….. | DRD 3 ….. | ….. | DRD x …..

1. Scientific and Resource Reporting and Review by a Detector Research and Development Committee (DRDC)

   Assisted by the ECFA Detector Panel (EDP): the scope, R&D goals, and milestones should be vetted against the vision encapsulated in the Roadmap

2. Funding Agency involvement via a dedicated Resources Review Board (~once every two years)

3. Yearly follow-up by DRDC➔ report to SPC (CERN Scientific Policy Committee) ➔ Council

- As projects develop, **some aspects should be expected to transition into approved experiment- specific R&D** (outside the DRD programme)

- In addition, as stated in the General recommendations (GSR7) funding possibilities for **"Blue-sky" R&D** should be foreseen

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