PSD13

St. Catherine's College
September 3-8, 2023

UNIVERSITY OF OXFORD

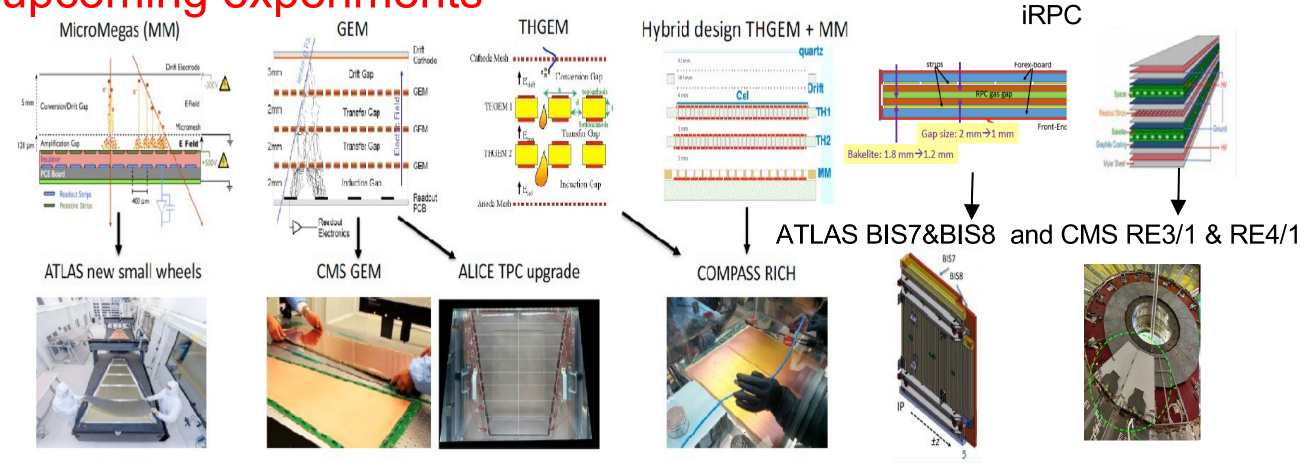
Gas Based Detectors

Anna Colaleo
University and INFN Bari

Embracing the Renaissance of Gaseous Detectors

Boosting the LHC upgrade and upcoming experiments

- enhancing Muon Tracking and Triggering with MPGDs, iRPC
- new Generation TPCs with MPGD-Based Readouts@ALICE/T2K
- ex.New Cylindrical Drift Chambers for MEGII, Novel StrawTubes at Mu2e, COMETI/II, Panda/@Fair...

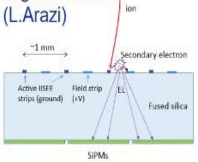


Offering competitive performance

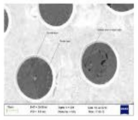
- Time Precision with MRPC@Alice TOF and PICOSEC concept

Pioneering Approach: New technologies, Materials, Architectures, and Hybrid Technology

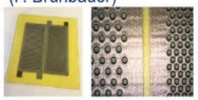
Positive Ion Detection in gaseous TPC (L.Arazi)



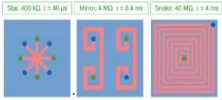
Charge transfer properties through graphene (P.Thuiner)



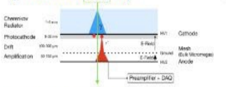
3D printed THGEM (F. Brunbauer)



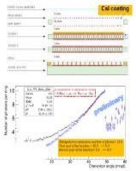
Scream mm (M. Chefdeville)

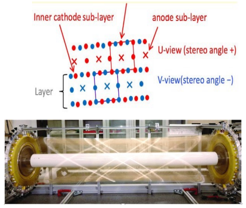


PICOSEC mm (PICOSEC coll.)

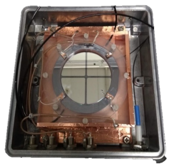


COMPASS RICH-1 (Compass)

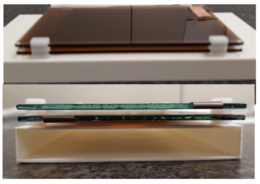




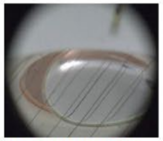
Caldarelli/Aielli single gap semi-conductor RPC



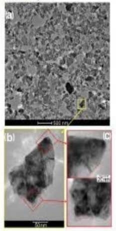
sRPC (Bencivenni



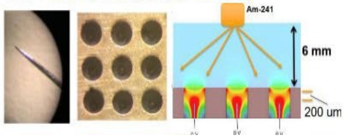
Bubble-assisted Liquid Hole-Multipliers (E. Erdal)



Nanodiamond photocathode (A. Valentini)



TIP-HOLE prototype (M. Cortesi)



uRWELL (G. Bencivenni)

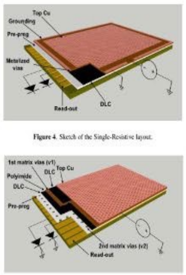
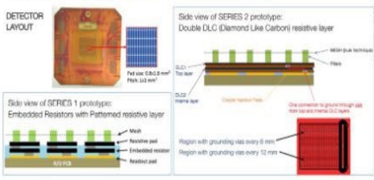
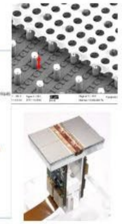


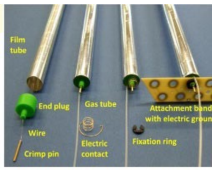
Figure 4. Sketch of the Single-Resistive layout.

Small pad resistive mm (M. Iodice)



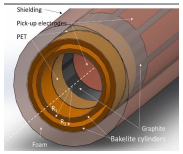
GridPix (J. Kaminski)



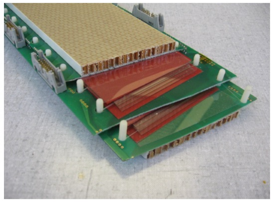


Straw tube components (for PANDA-STT [1])

RCC Caldarelli



ALICE MRPC



Gaseous detectors at LHC

	Vertex	Inner Tracker	PID/ photo-det.	EM CALO	HAD CALO	MUON Track	MUON Trigger
ATLAS	-	TRD (straws)	-	-	-	MDT (drift tubes), CSC,	RPC, TGC,
CMS **TOTEM**	-	-	-	-	-	Drift tubes, CSC GEM	Drift tubes, CSC GEM
LHCb	-	Straws →SciFi	-	-	-	MWPC	MWPC, GEM
ALICE	-	TPC (MWPC→ Upgrade to 4-GEM)	TOF(MRPC), PMD, HPMID (RICH-pad chamber), TRD (MWPC)	-	-	Muon pad chambers	RPC


CMS DT + RPC


ATLAS TRD -straw


ATLAS TGC


ALICE MRPC

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)

Gaseous detector upgrade at HL-LHC

M.Titov

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

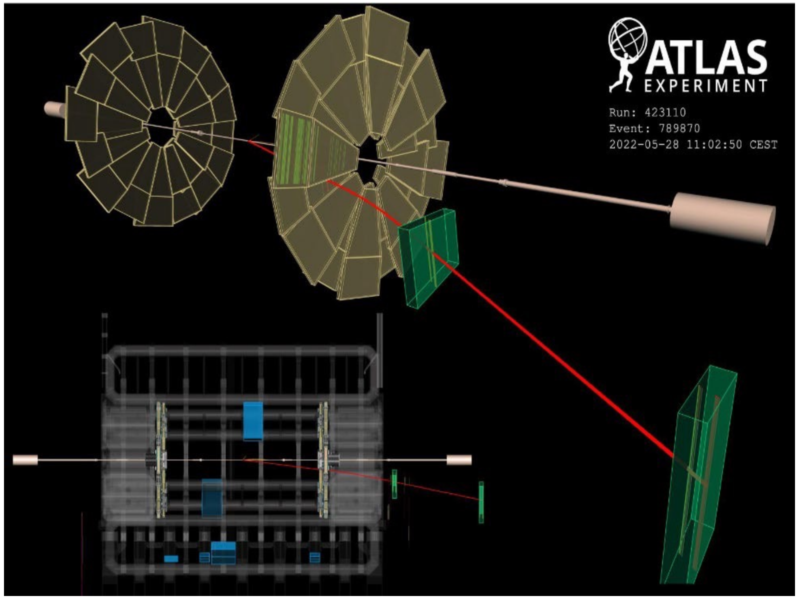
MPGD: Unveiling Inaugural Findings from Run 3

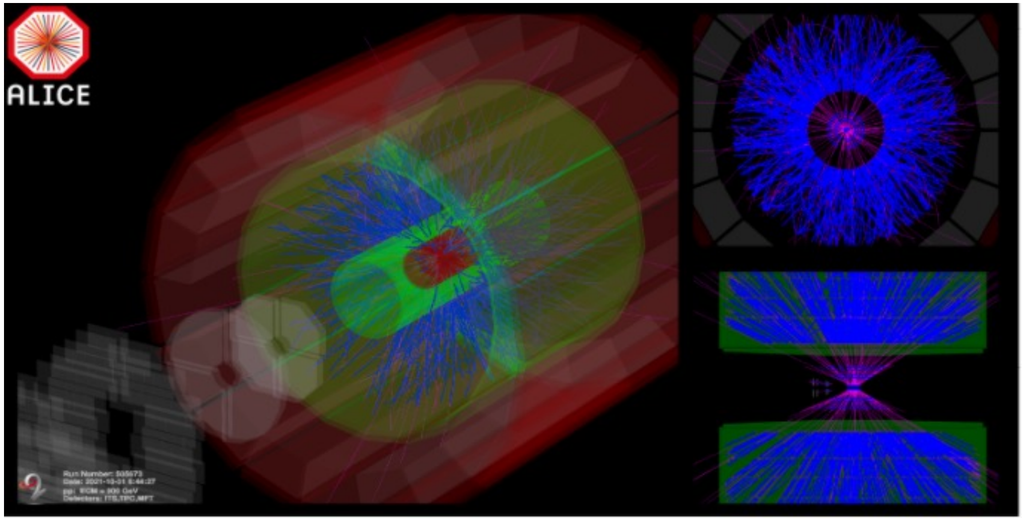
Advancements in MPGDs:

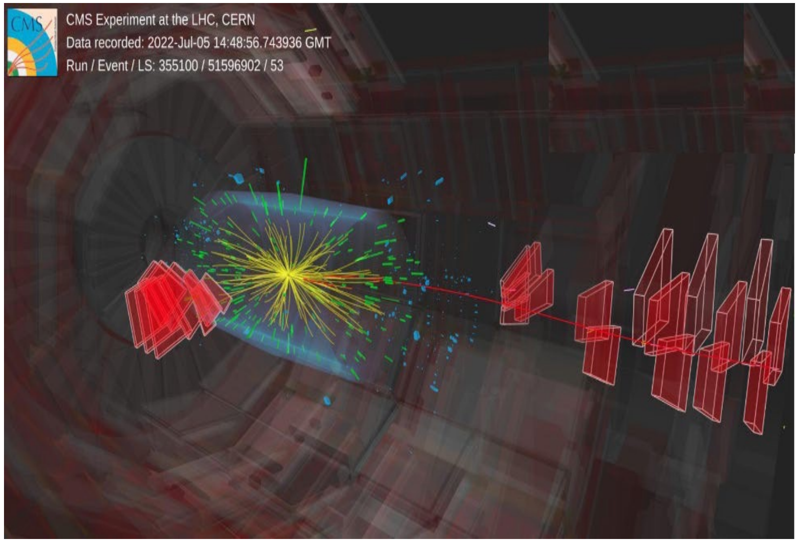
Fueling ATLAS, CMS, ALICE Upgrades in Run 3

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







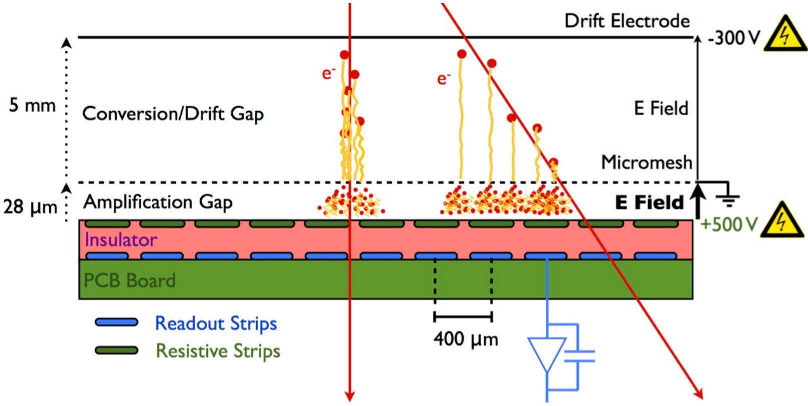
MPGD: Unveiling Inaugural Findings from Run 3

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

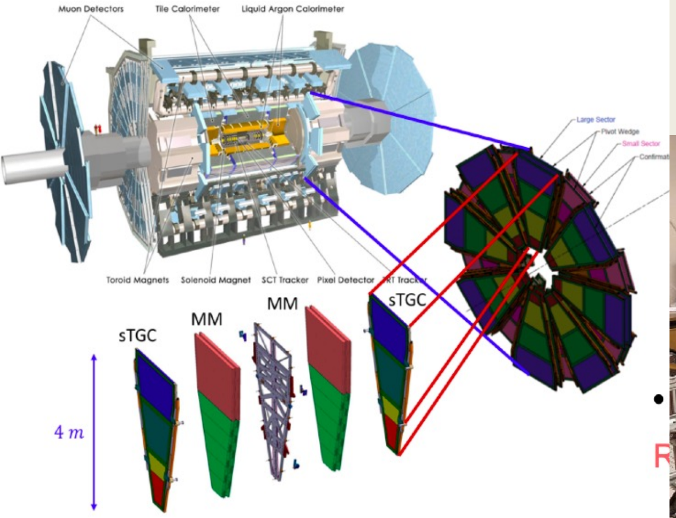
- Precision tracking (~ 100 μm/plane, > 90% efficiency) for $\sigma p_t/p_t < 15\%$ at muon $p_T \approx 1$ TeV
- particle flux: up to 20 kHz/cm^2 rejecting fake triggers.

Peculiarities of ATLAS NSW Muon Upgrade's Resistive MM:

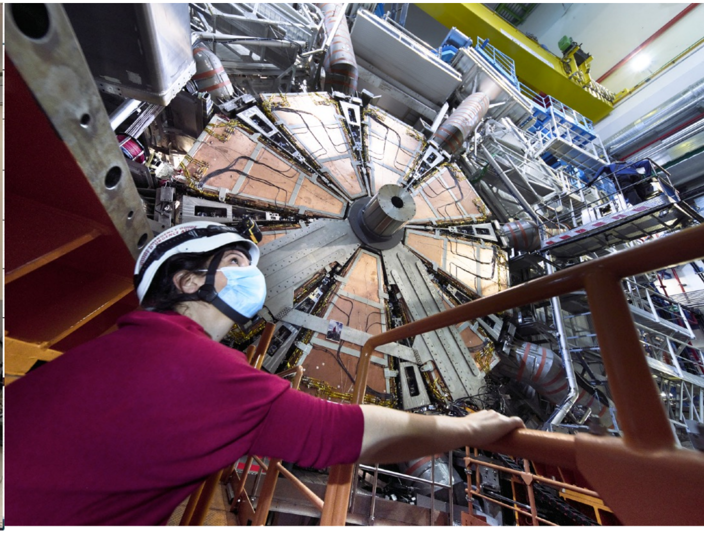
- Screen-printed resistive strips capacitive-coupled to Cu strips.
- Araldite passivation on edges for uniformity, less edge effects.
- Thin metallic micro-mesh at ground potential.
- "Floating" mesh integrated in drift panel
- Operates at -60 V with 93/5/2% Ar/CO2/isobutane mixture.



1200m² resistive MM: installation ended beginning 2022

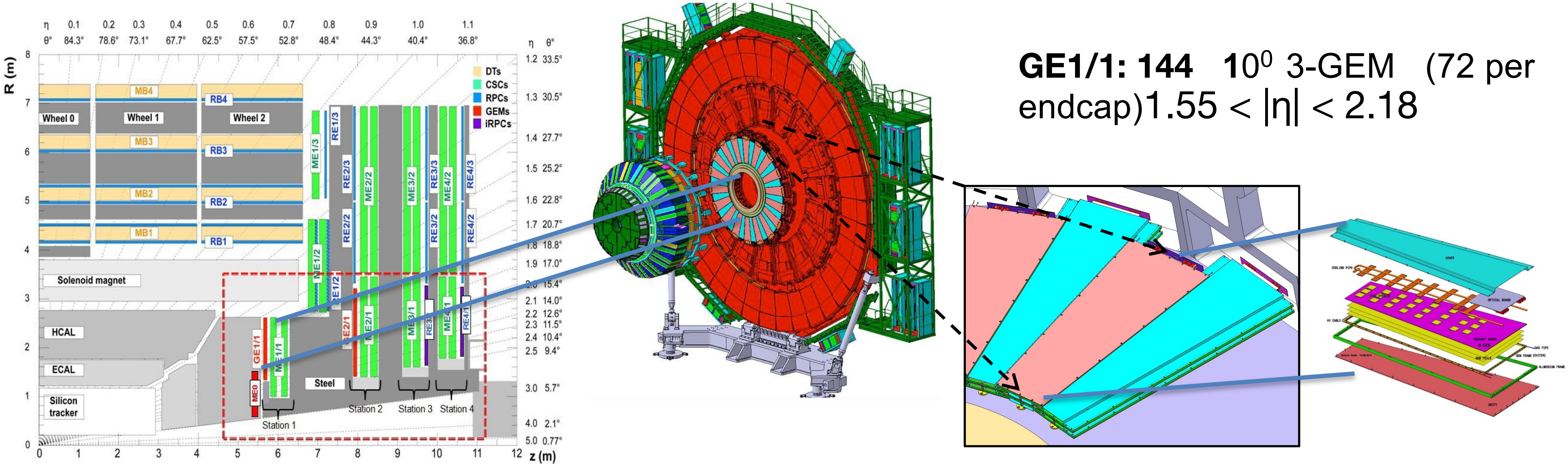


Read-out strip positions need < 30 μm accuracy. Chamber position within 80 μm accuracy➔ A granite table 8 um precision



MPGD: Unveiling Inaugural Findings from Run 3

3GEM+ Cathode Strip Chambers (CSC) allows for muon momentum measurement in a single station, which helps reduce considerably L1 trigger rate@ HL-LHC

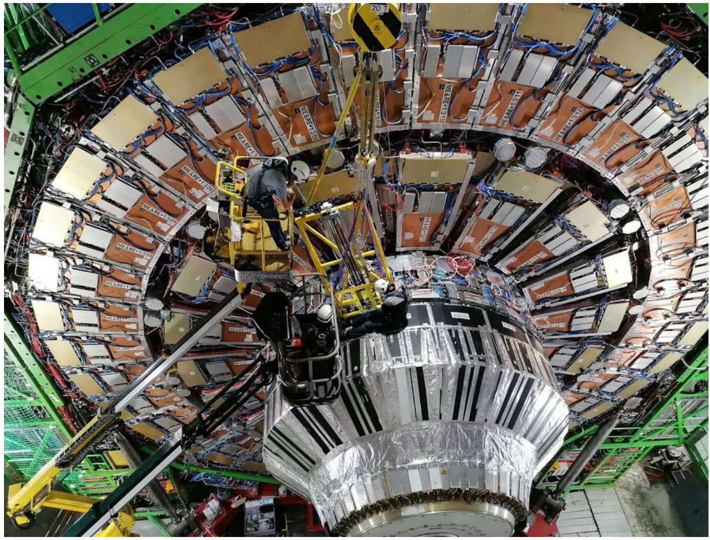


GE1/1: 144 **10^0** 3-GEM (72 per endcap) $1.55 < |\eta| < 2.18$

CMS triple-GEM detectors peculiarities:

- 3/1/2/1 mm gaps
- Single-mask GEM technology
- mechanical foil stretching technique
- 15-years-long R&D on design, components and materials (longevity, outgassing studies, etc.)

- High rate O(MHz/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

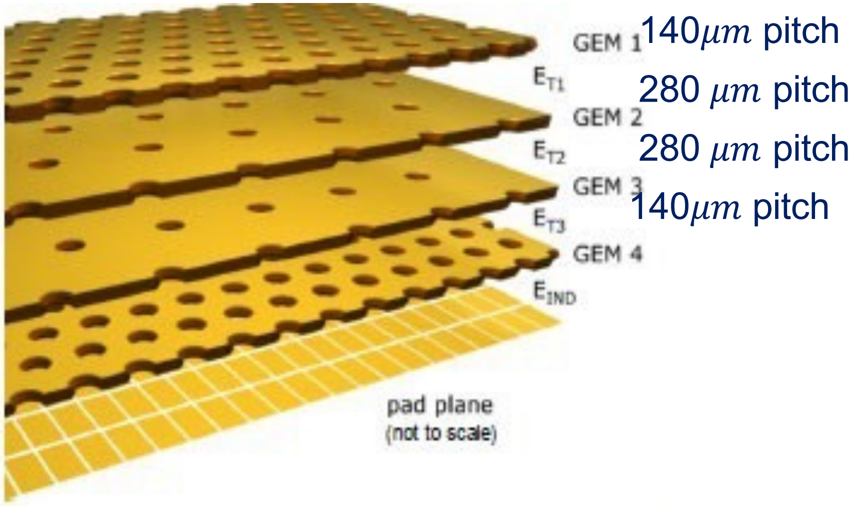
MPGD: Unveiling Inaugural Findings from Run 3

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

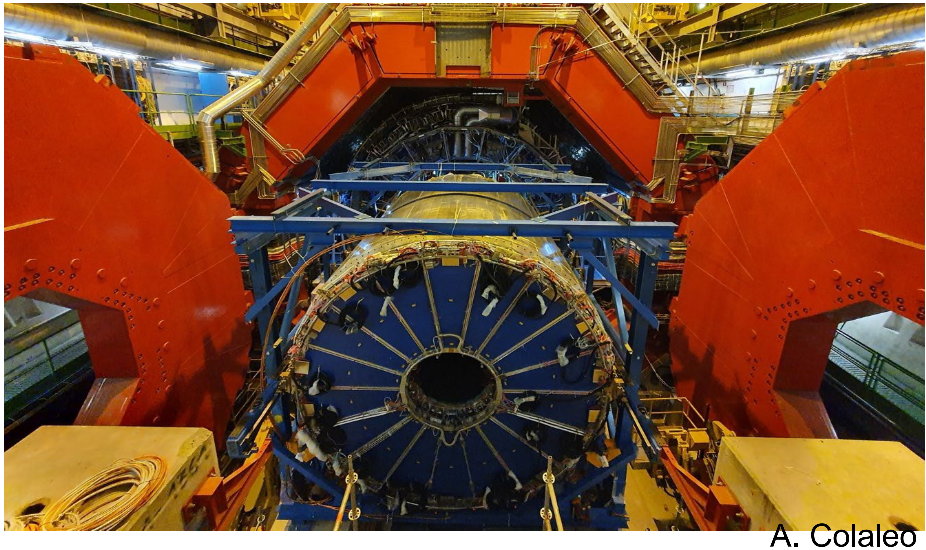
➔ choice of 4-GEM

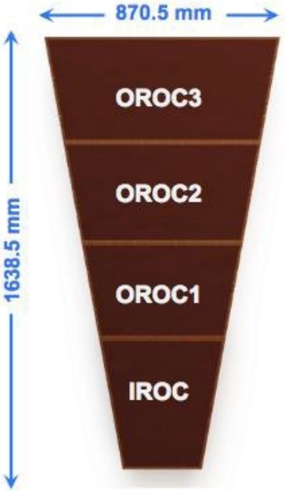
- Total effective gain ~ 2000
- Energy res. σ(E)E < 12%
- Intrinsic ion-blocking capabilities (IB <1%)
- Keep space-charge distortions at a tolerable level
- Mixture Ne-CO2-N2 (90-10-5) (high ion mobility)

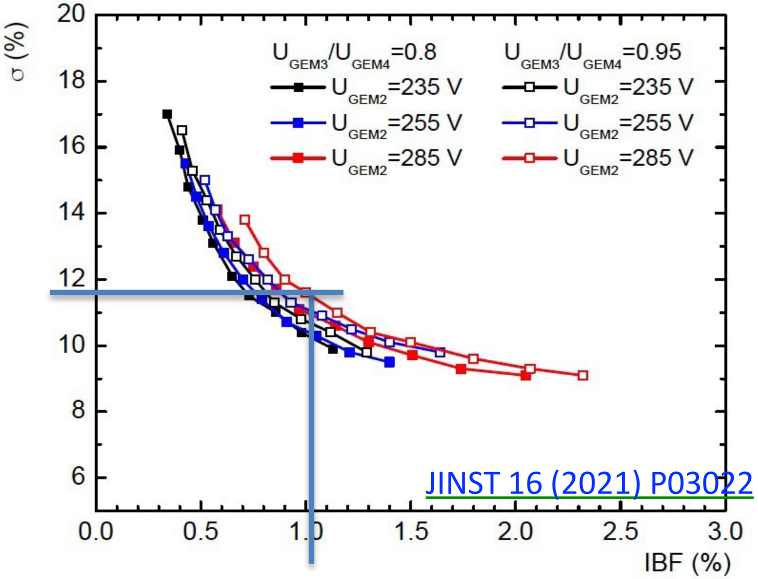
R&D synergies between the ILC TPC and the T2K-II ND TPC.



TPC reinstallation in the ALICE cavern (August 2020)







JINST 16 (2021) P03022

Steps toward a long term detector R&D program

2019
Granada Symposium
WGs and Physics Briefing Book

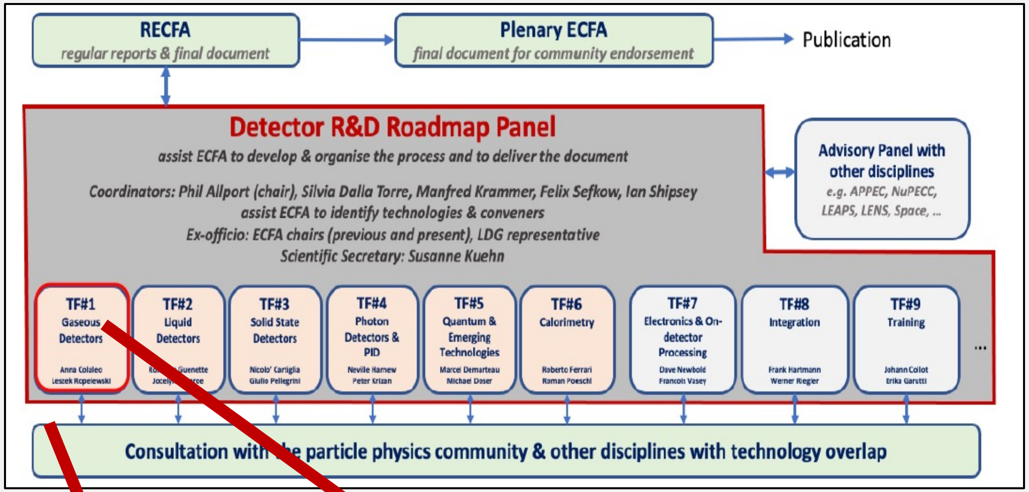
ESPP update
HEP strategic projects
2020

2021
ECFA detector R&D roadmap
TF & community workshops

ECFA DRD proposals
2023

2024
DRD MoUs
collaborations active

ESPP update
2026-27



RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement

Publication

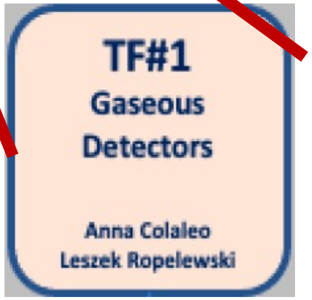
Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document
Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, ...

- **TF#1** Gaseous Detectors – Anna Colaleo, Leszek Ropelewski
- **TF#2** Liquid Detectors – Ro Guenette, Jocely roe
- **TF#3** Solid State Detectors – Nicolo' Cartiglia, Giulio Pellegrini
- **TF#4** Photon Detectors & PID – Neville Harnew, Peter Krizan
- **TF#5** Quantum & Emerging Technologies – Marcel Demarteau, Michael Doser
- **TF#6** Calorimetry – Roberto Ferrari, Roman Poeschl
- **TF#7** Electronics & On-detector Processing – Dave Newbold, Francois Vasey
- **TF#8** Integration – Frank Hartmann, Werner Riegler
- **TF#9** Training – Johann Collot, Erika Garutti
- ...

Consultation with the particle physics community & other disciplines with technology overlap

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)



TF#1
Gaseous Detectors
Anna Colaleo
Leszek Ropelewski

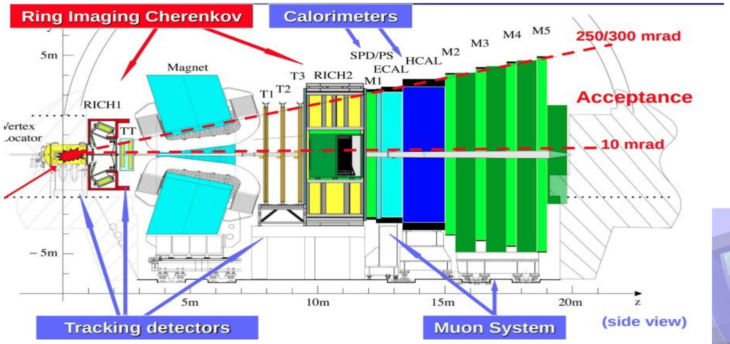
Conveners: A.C, , Leszek Ropelewski (CERN)

Experts: Klaus Dehmelt (SUNY), Barbara Liberti (INFN-Rome2), Maxim Titov (CEA Paris-Saclay), Joao Veloso (Univ. Aveiro)

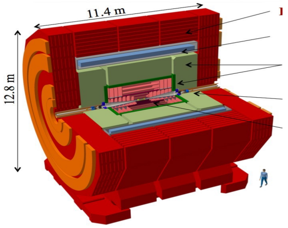
Link to the coordination team : Silvia Dalla Torre (INFN-Trieste)

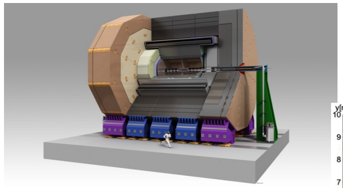
Main target projects of Gaseous Detector R&D

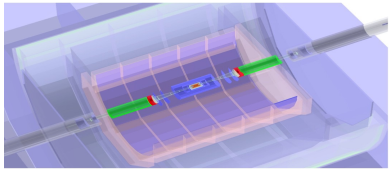
HL-LHC after LS4

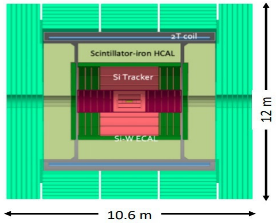


Higgs Factories

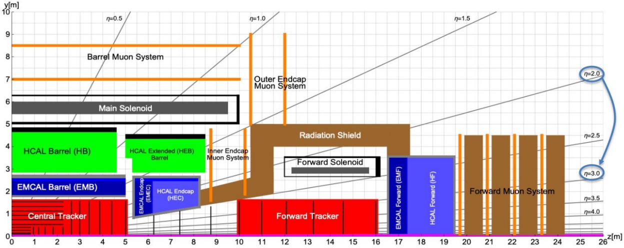




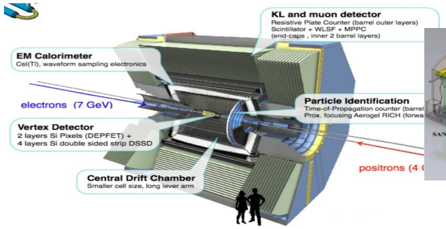


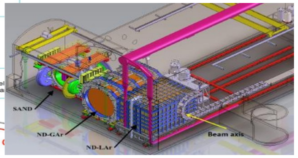


Future hadron colliders (FCC-hh/eh colliders)



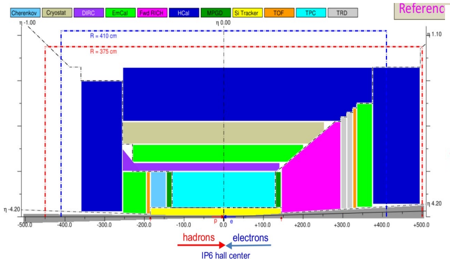
SuperKEKB, DUNE ND



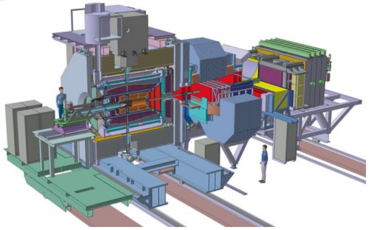


Hadron physics

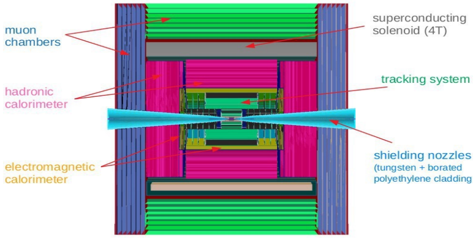
EiC



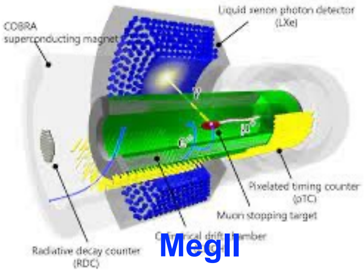
PANDA



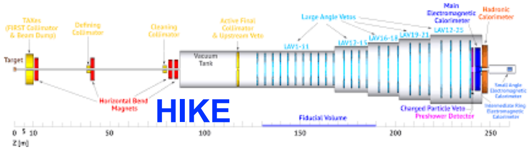
Muon Collider



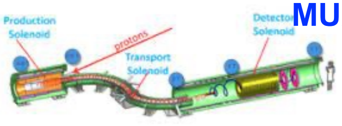
Rare event search, fixed target (LFV, Kaon physics)



MegII



HIKE



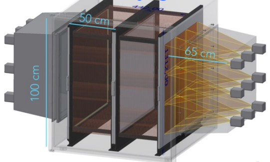
MU2E

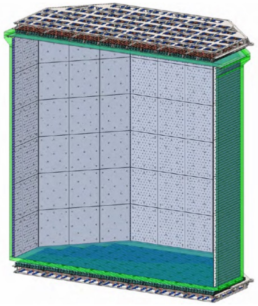
DM, solar axions, ββ0ν-decay, neutrino, nuclear, astroparicle

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Darksphere

Cygnus

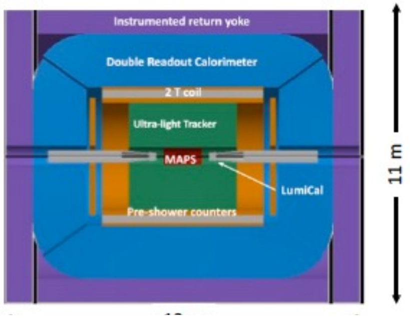




DarkSide20 and ARGO

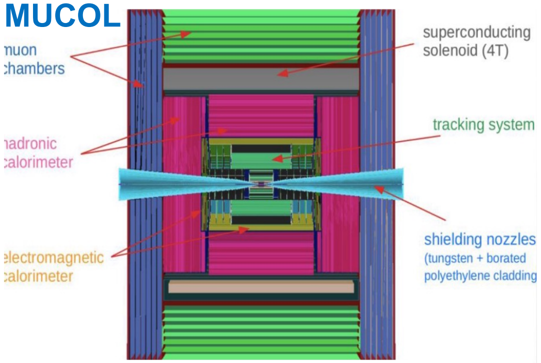
Muon system: ex. FCC-ee/CEPC/Muon Collider

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 res, σ_x, of O(100)um

Efficiency ~ 98-99%

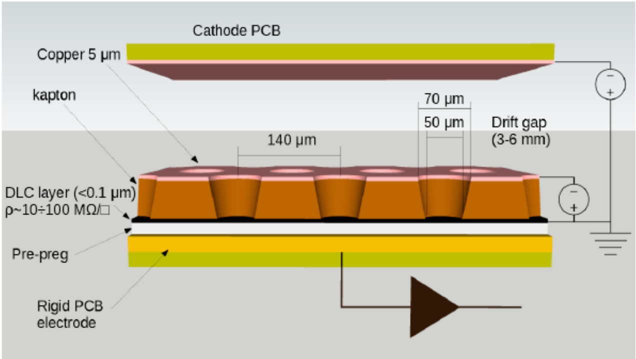
Time res.: <ns (trigger/BX-id, bkg rej, LPP..)

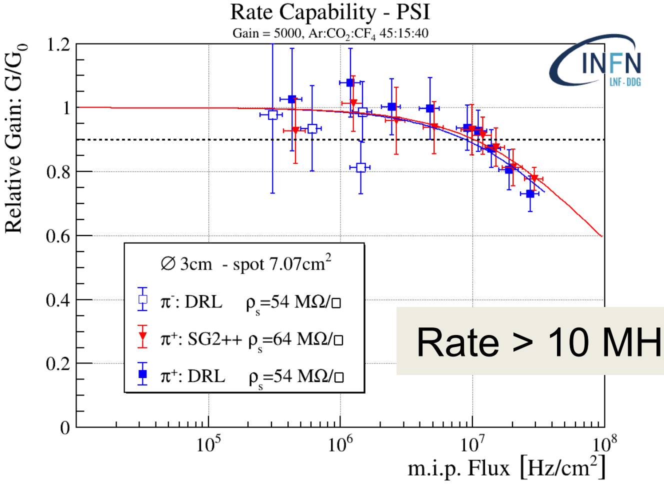
Rate: few KHz/cm^2 – MHz/cm^2

Low GWP gas mixture

G.Benciventni

µRWell

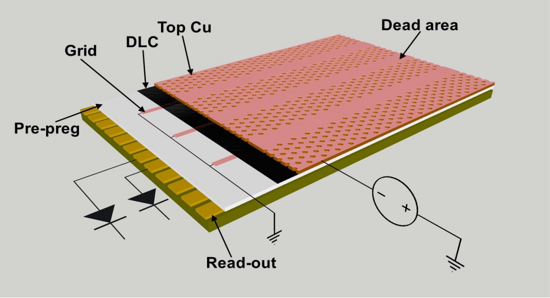




Rate > 10 MHz/cm^2

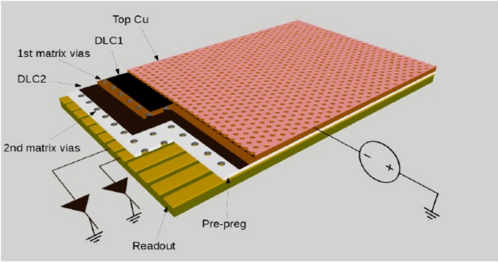
- RPC -30 × 30 mm^2 cells @CLD/CEPC
- MPGD/RPC@ Muon collider
- µRWell 50x50 cm^2 (tiles) also for pre-shower @FCC

@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)

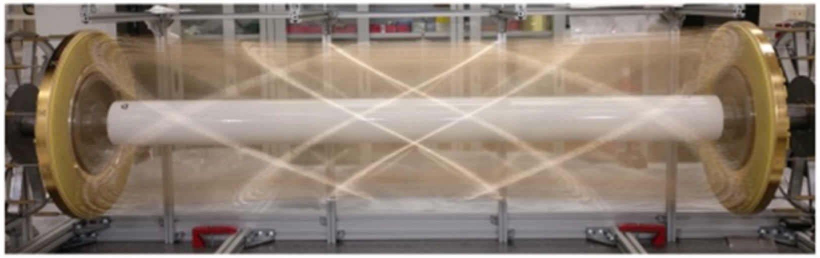


Double resistive layer (DRL)

- Double DLC layers connected through matrices of conductive vias to the readout electrodes

Inner & central tracking with PID: Drift chambers

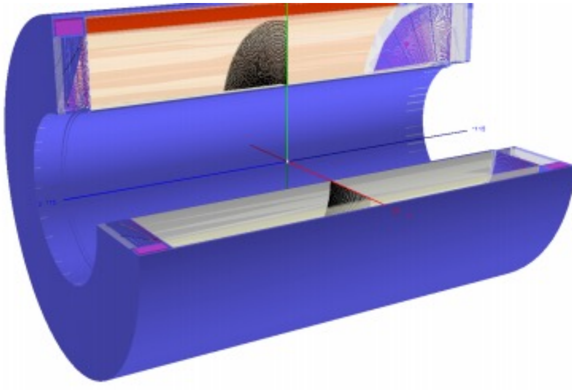
Approach at construction technique of high granularity and high transparency Drift Chambers@ **FCC-ee/CEPC/SCTF ➔ Main studies for IDEA cylindrical drift chamber (DCH)**



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

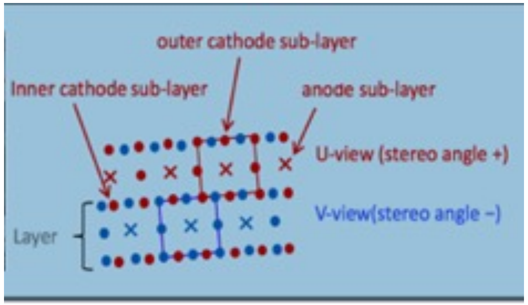
- High wire number requires a non standard wiring procedure and needs a feed-through-less wiring system.
- A novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber



☐ GAS: 90% He – 10% iC_4H_{10}

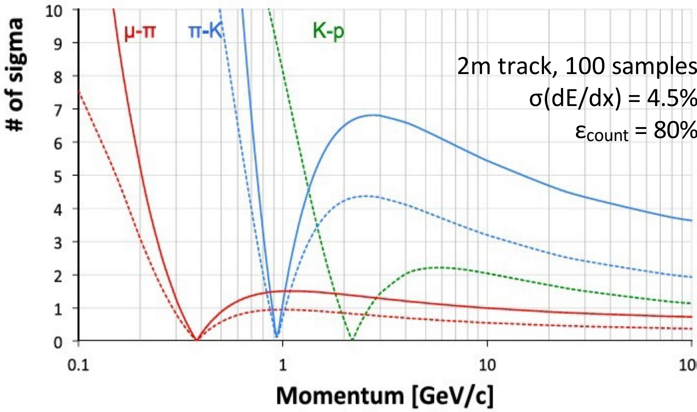
☐ Radius 0.35 – 2.00 m

☐ Total thickness: 1.6% of X_0 at 90°



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

Particle Separation (dE/dx vs dN/dx)



The dE/dx < 3% , momentum resolution: $\sigma(p_T)/p_T \approx 0.4\%$ 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 chambers

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.

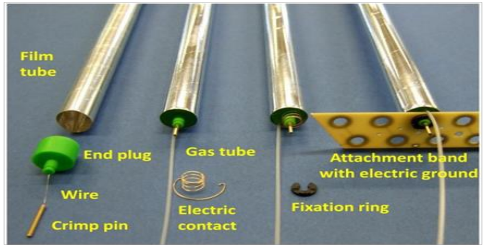
NA62 is the state-of-the-art straw tracker

- Breakthrough: 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/X0

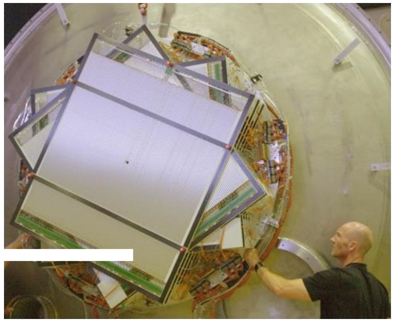
P. Wintz

	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 development	Planned
Specific R&D	Vacuum tracker	Low X/X0 solenoid tracker	Vacuum tracker	Thinnest wall vacuum tracker		Long straws in vacuum

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



NA62 Straw station

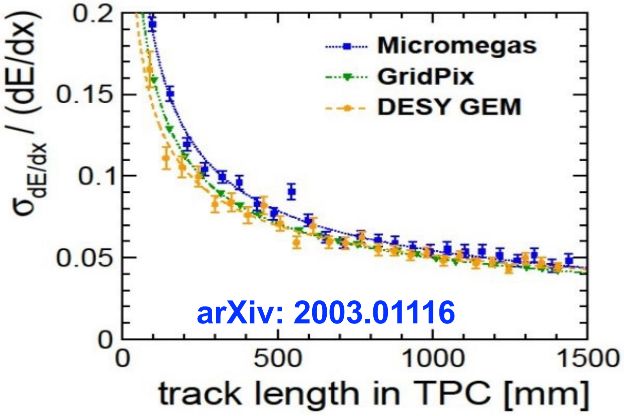


COSY-TOF Straw tracker

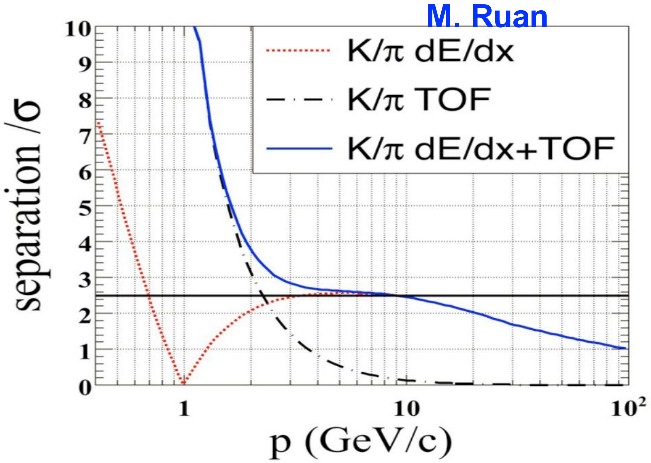
Inner/Central tracking with PID: TPC with MPGD-based Readout

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

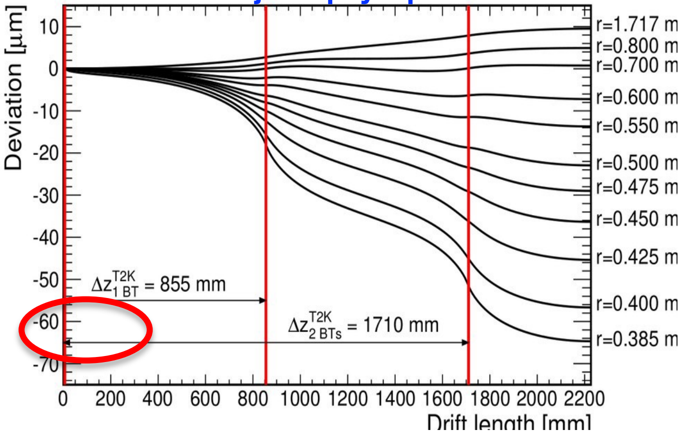


arXiv: 2003.01116



M. Ruan

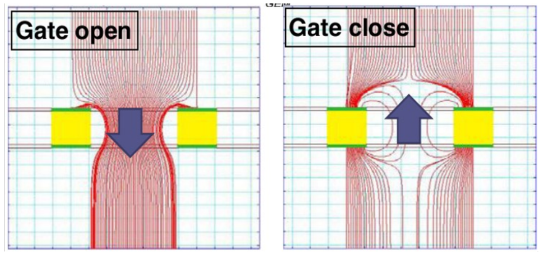
10.1016/j.nuclphysbps.2015.09.174



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

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

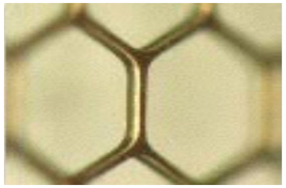
Gas amplification 10^3 ➔distortions of 60 μm ➔ gating device is needed



➔ 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:

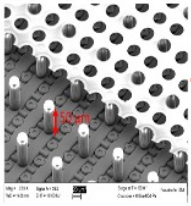
- Measured electron transparency >80 % (as in simulations) for ΔV ~ 5V



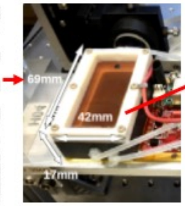
Inner/Central tracking with PID: TPC with MPGD-based Readout

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

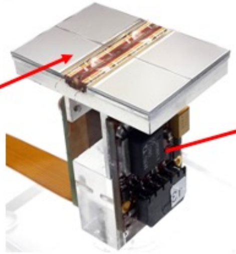
- **HZ/WW/tt running➔** Pad readout (MM + GEM)
- **Z pole running**(@10^{36}): primary ion density 1000 ions/cm^3
  ➔ tracks distortions O(mm) ➔ Pixelated readout ➔ GridPix
  - ✓ Single ionisation electrons are detected with high efficiency
  - ✓ dE/dx by cluster counting
  - ✓ Measuring IBF for Gridpix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



MM grid (InGrid) on Timepix chip

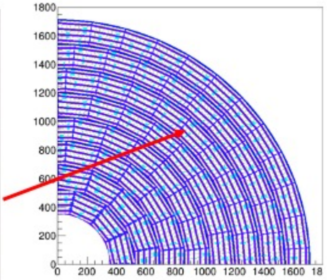


Single chip 2017

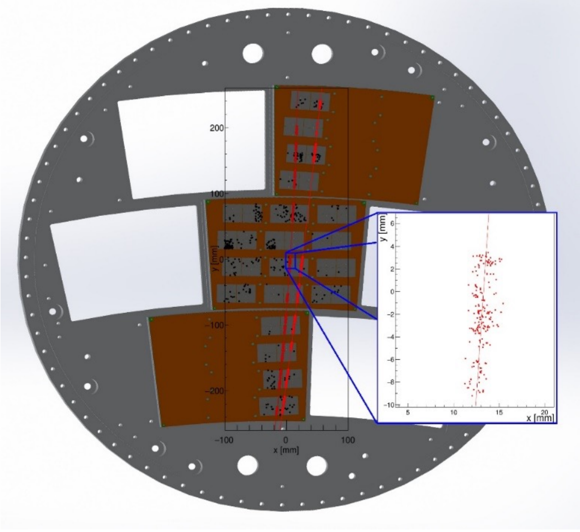


Quad 2018

Module - 2019



TPC plane

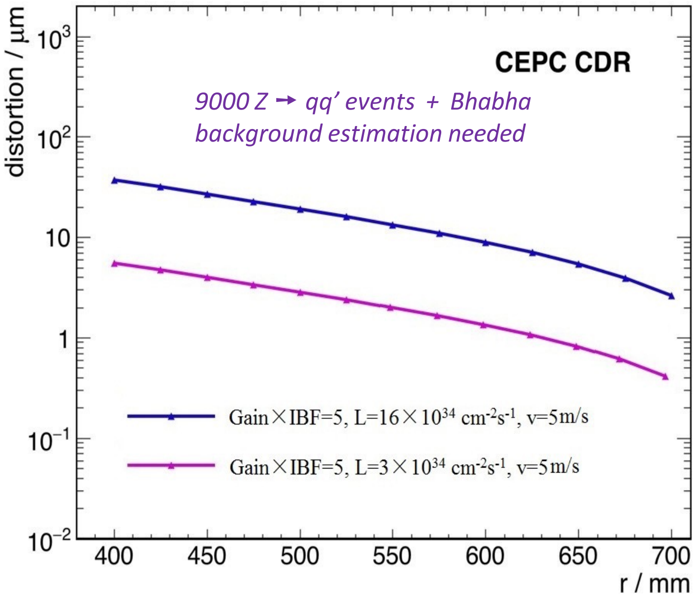


The maximum possible information from a track is acquired:

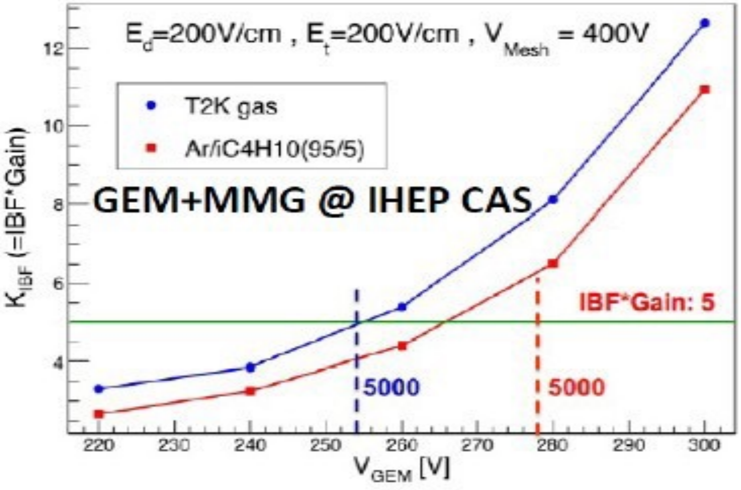
50 cm track length with ~ 3000 hits

→ 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



Calorimeter

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:

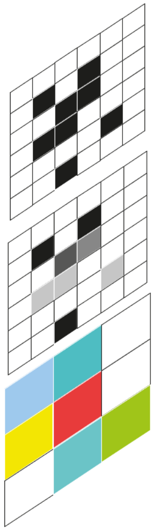
Studies done within CALICE collaboration:

- AHCAL Scint+SiPM 3 x 3 cm^2 granularity
- DHCAL glass RPC 1 x 1 cm^2 granularity
- SDHCAL RPC/MICROMEGAS/RPWELL 1 x 1 cm^2 granularity

New handle: Fast- timing

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

Facilities: (ILC/C^3, FCC-ee, CEPC, Muon collider, Hadron Physics).

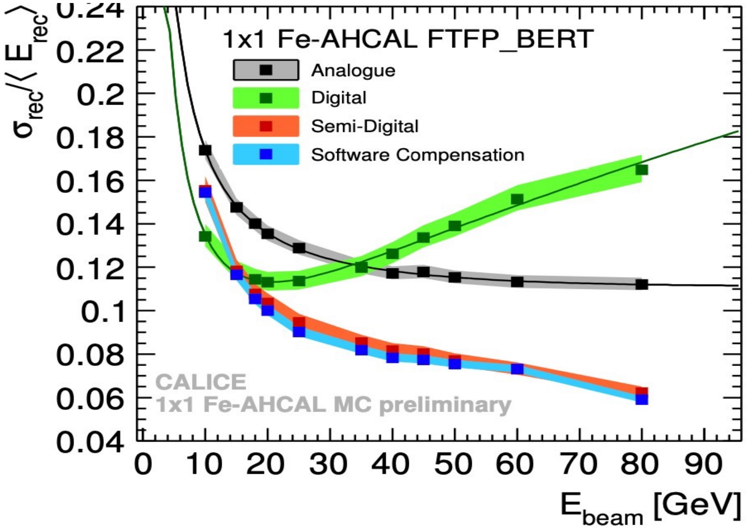


“digital”
counting hit cells

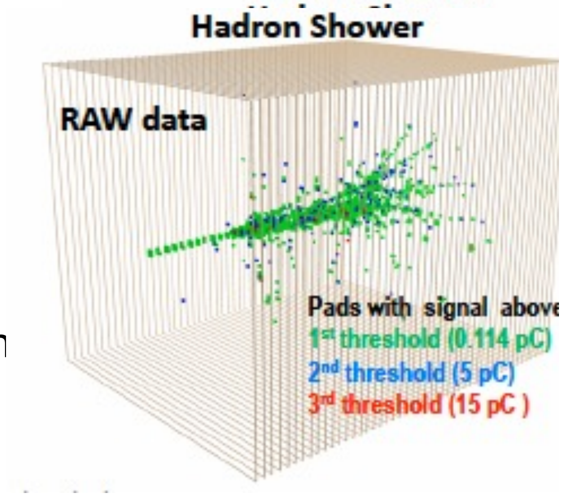
“semi-digital”
2 bits per cell:
one, a few, many particles

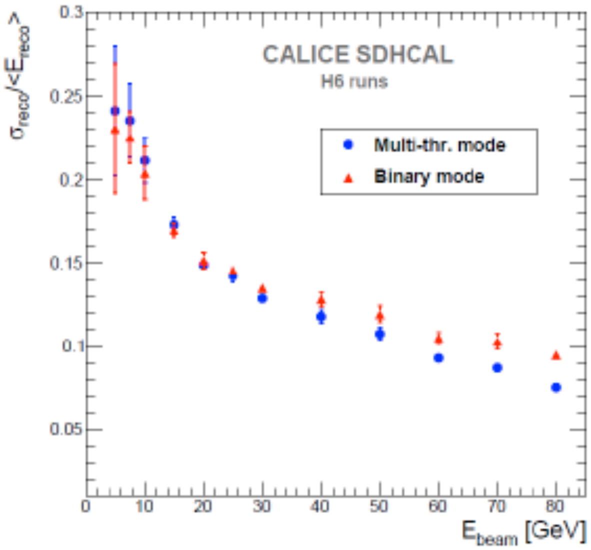
“analog”
full analog information
typically 14+ bits

F. Simon



➔ 1x1 cm^2 pad: energy resolution in SDHCAL same as AHCAL with software compensation





Large area Fast timing gaseous detectors

Multi-Gap Resistive Plate Chambers (MRPC):

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

Z.Liu

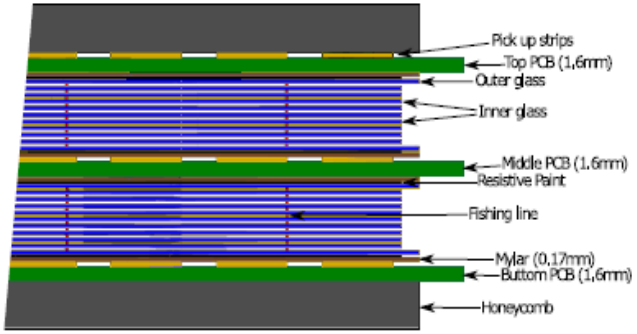
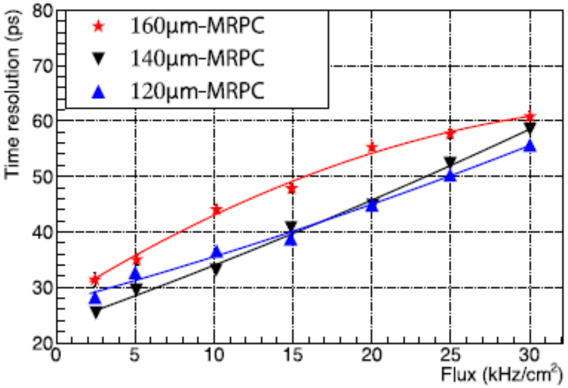
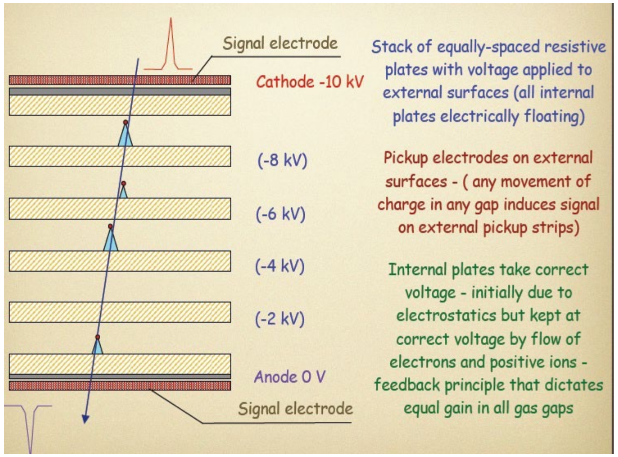


Fig. 1. Cross section of the double stack 20-gap MRPC.





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

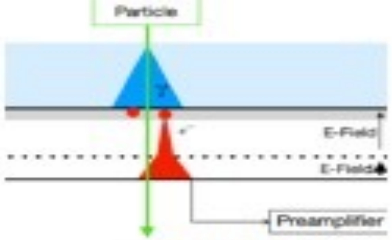
Pickup electrodes on external surfaces - (any movement of charge in any gap induces signal on external pickup strips)

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

Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

E. Oliveri

σ ~ 25 ps timing resolution (per track)



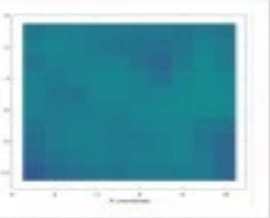
24ps timing resolution

Single pad (2016)
⌀1 cm

Cherenkov radiator + Photocathode + Micromegas

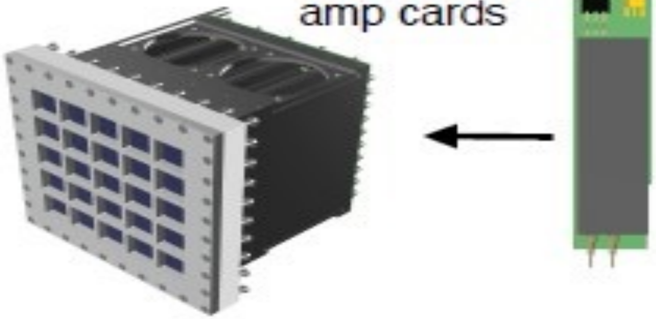
Tested in RD51 testbeam July 2021

10x10 module
▫ 1 cm



Planarity < 10µm

Custom pre-amp cards



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

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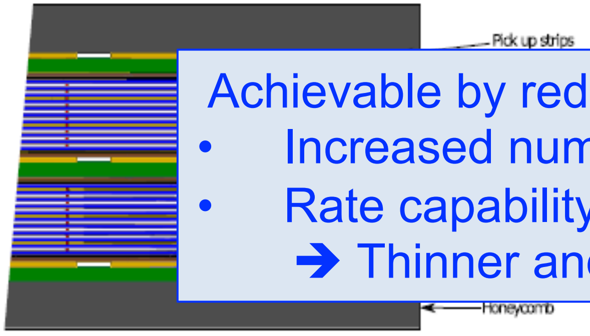
➔ down to 20 ps time resolution



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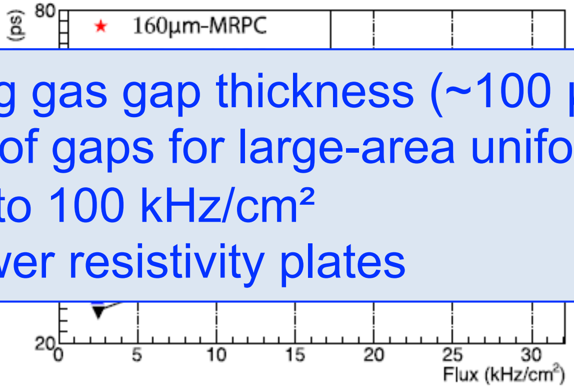
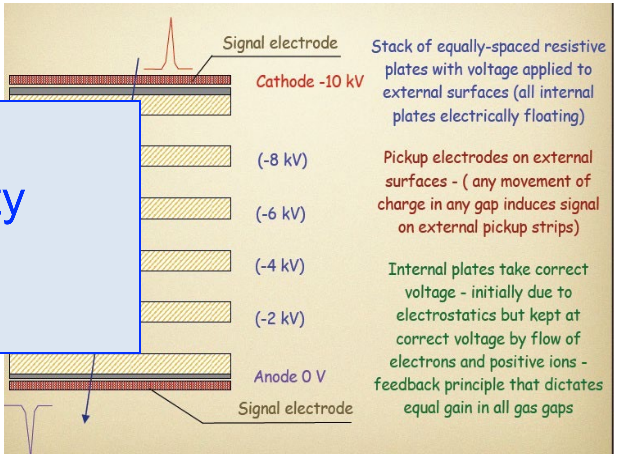


Achievable by reducing gas gap thickness (~100 μm)

- Increased number of gaps for large-area uniformity
- Rate capability up to 100 kHz/cm²

➔ Thinner and lower resistivity plates



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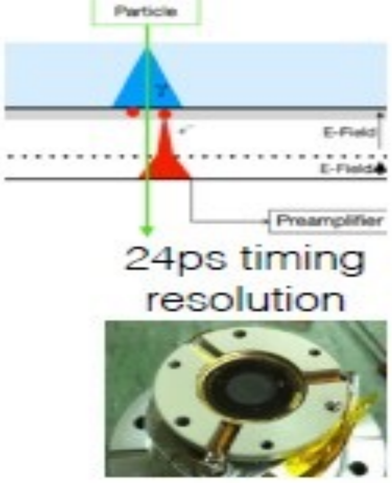
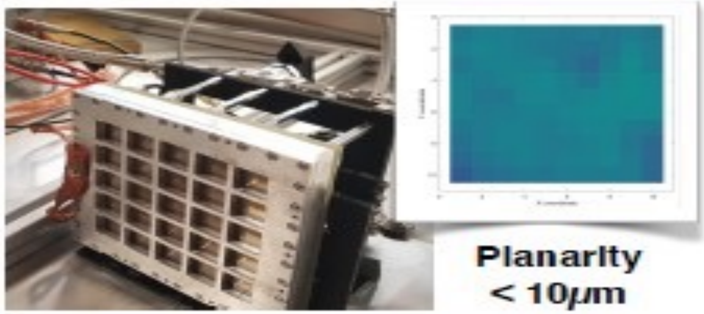


24ps timing resolution

Tested in RD51 testbeam July 2021



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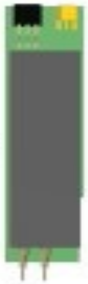
Custom pre-amp cards



Single pad (2016) ⌀1 cm

10x10 module ▫ 1 cm

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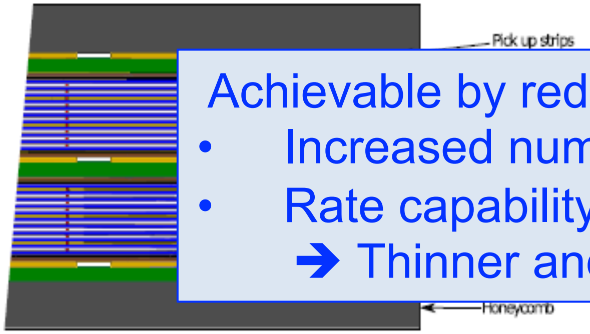
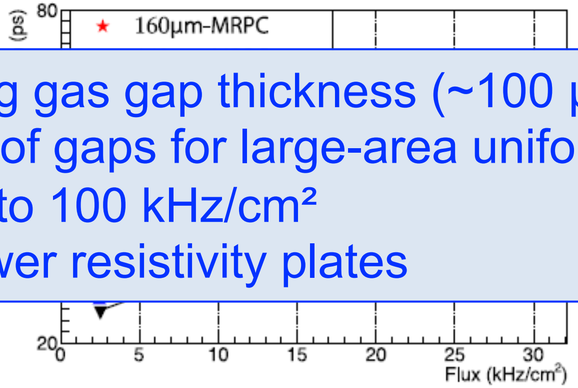
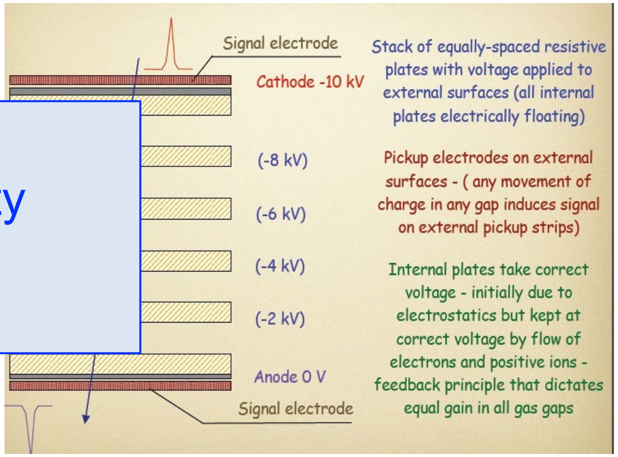


Fig. 1. Cross section of the double stack 20-gap MRPC.





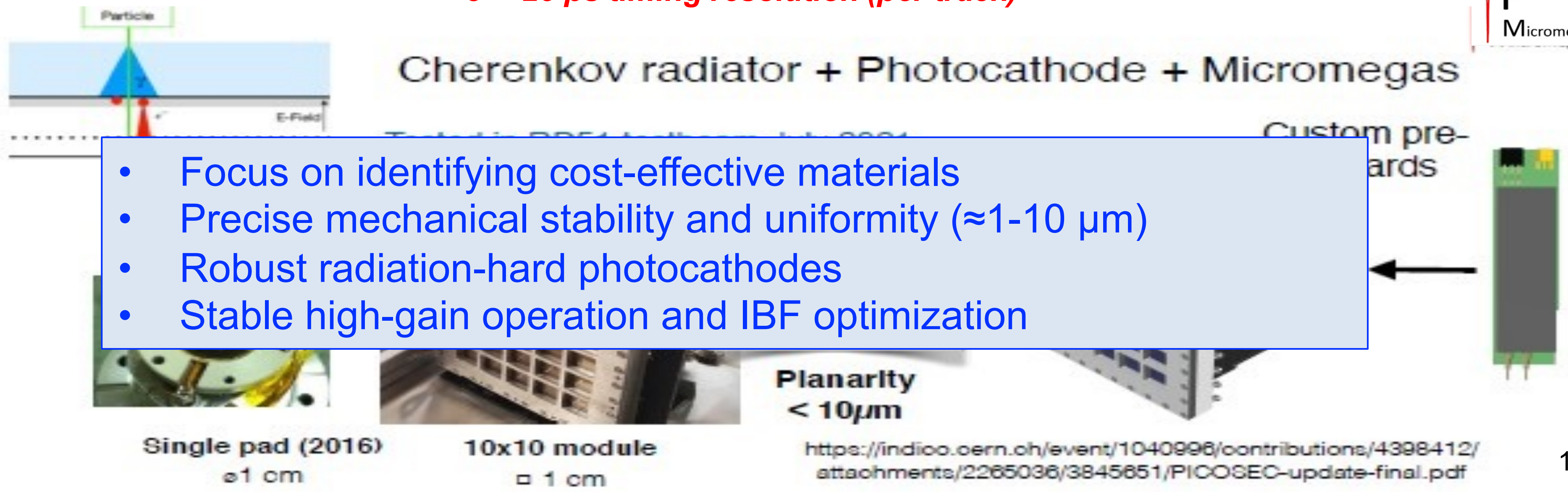
Achievable by reducing gas gap thickness (~100 μm)

- 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)

E. Oliveri

σ ~ 25 ps timing resolution (per track)



- 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

DRD1 Collaboration implementation

R&D FRAMEWORK

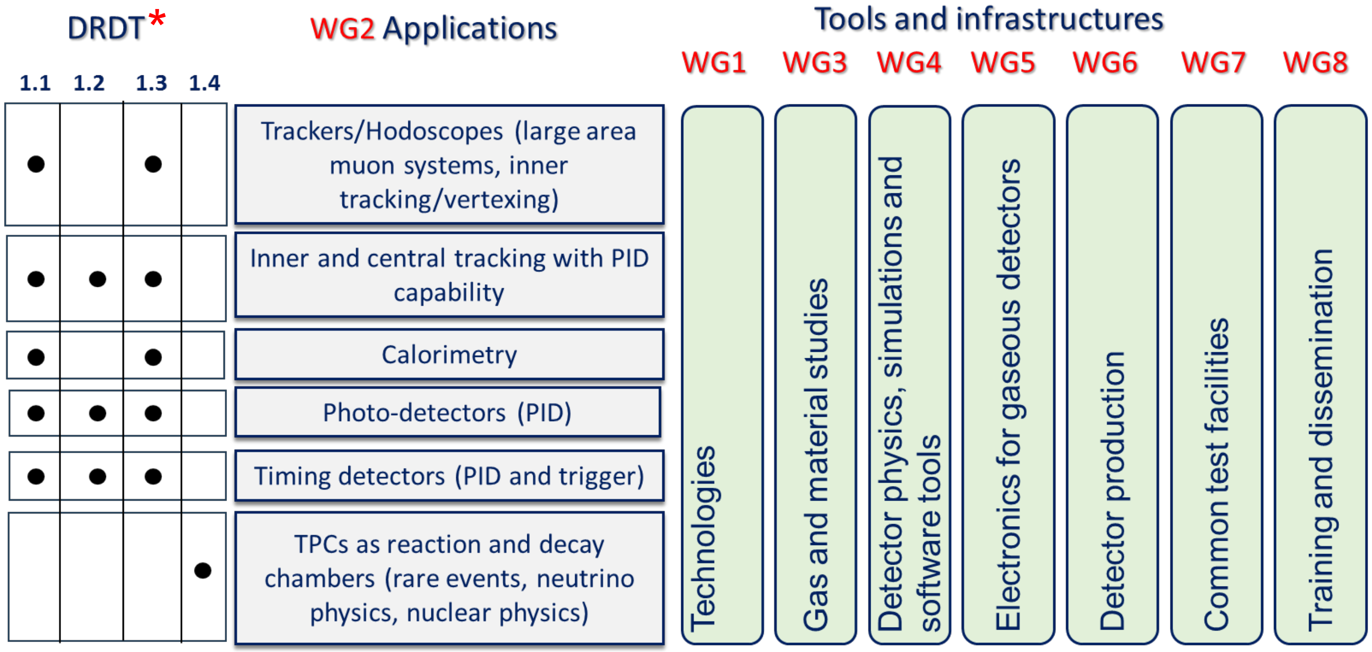
- **Collaboration type: Community-driven** with the **R&D environment:** common infrastructures (labs, workshops), common R&D tools (software and electronics), cross-disciplinary exchange

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

R&D PROJECTS

- **Work Packages (WP):** long-term **projects** addressing strategic R&D goals, **outlined in the ECFA Detector R&D roadmap** 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)

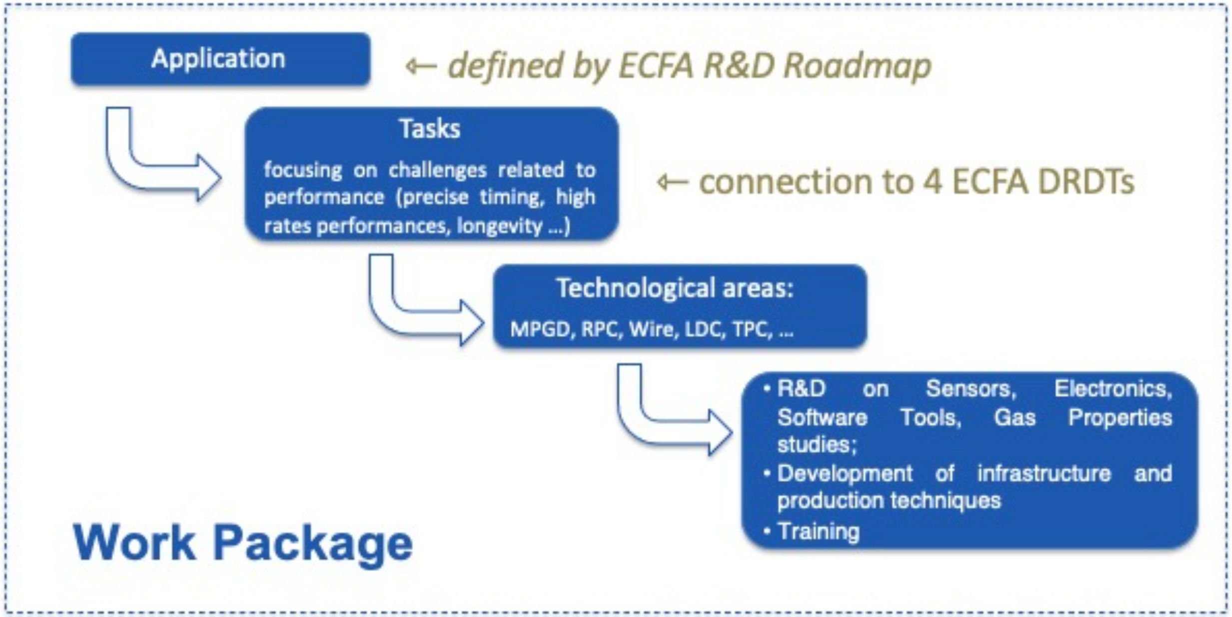
Tools and infrastructures

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

* See backup

Strategic R&D = Work Package

- **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 envisaged 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

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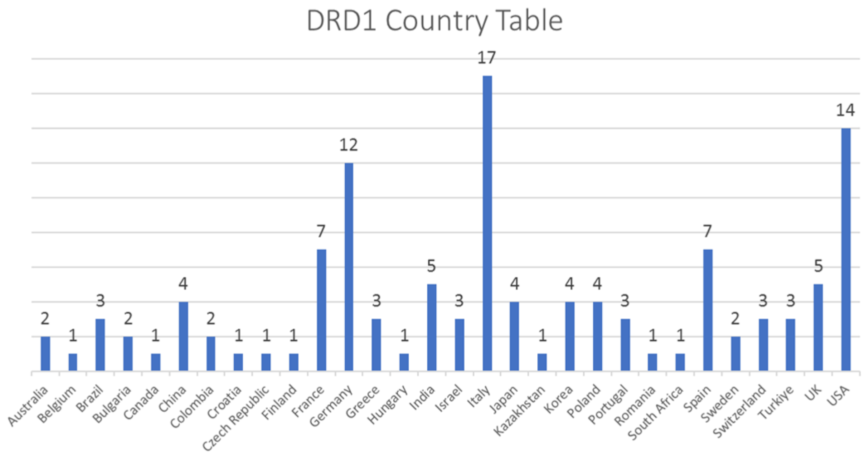
* DRDT: See backup

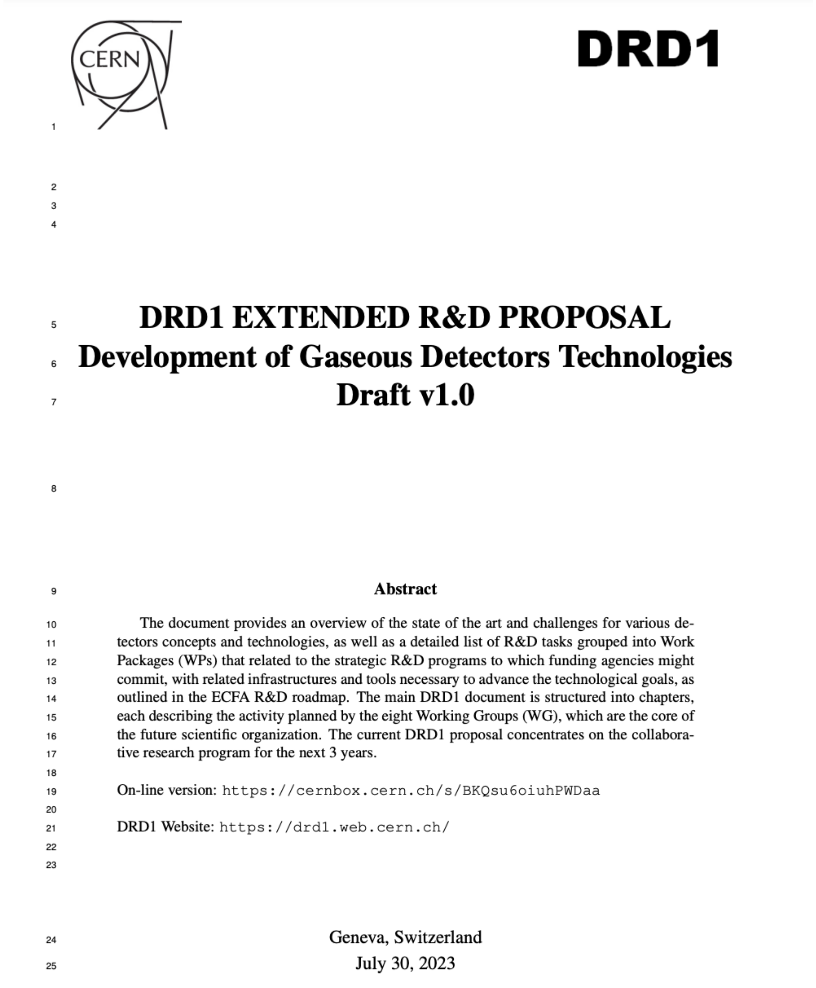
DRD1 PROPOSAL

https://drd1.web.cern.ch/

https://cernbox.cern.ch/s/BKQsu6oiuhPWDaa

Expression of interest form 118 institutes from 30 countries





CERN

DRD1

DRD1 EXTENDED R&D PROPOSAL
Development of Gaseous Detectors Technologies
Draft v1.0

Abstract

The document provides an overview of the state of the art and challenges for various detectors concepts and technologies, as well as a detailed list of R&D tasks grouped into Work Packages (WPs) that related to the strategic R&D programs to which funding agencies might commit, with related infrastructures and tools necessary to advance the technological goals, as outlined in the ECFA R&D roadmap. The main DRD1 document is structured into chapters, each describing the activity planned by the eight Working Groups (WG), which are the core of the future scientific organization. The current DRD1 proposal concentrates on the collaborative research program for the next 3 years.

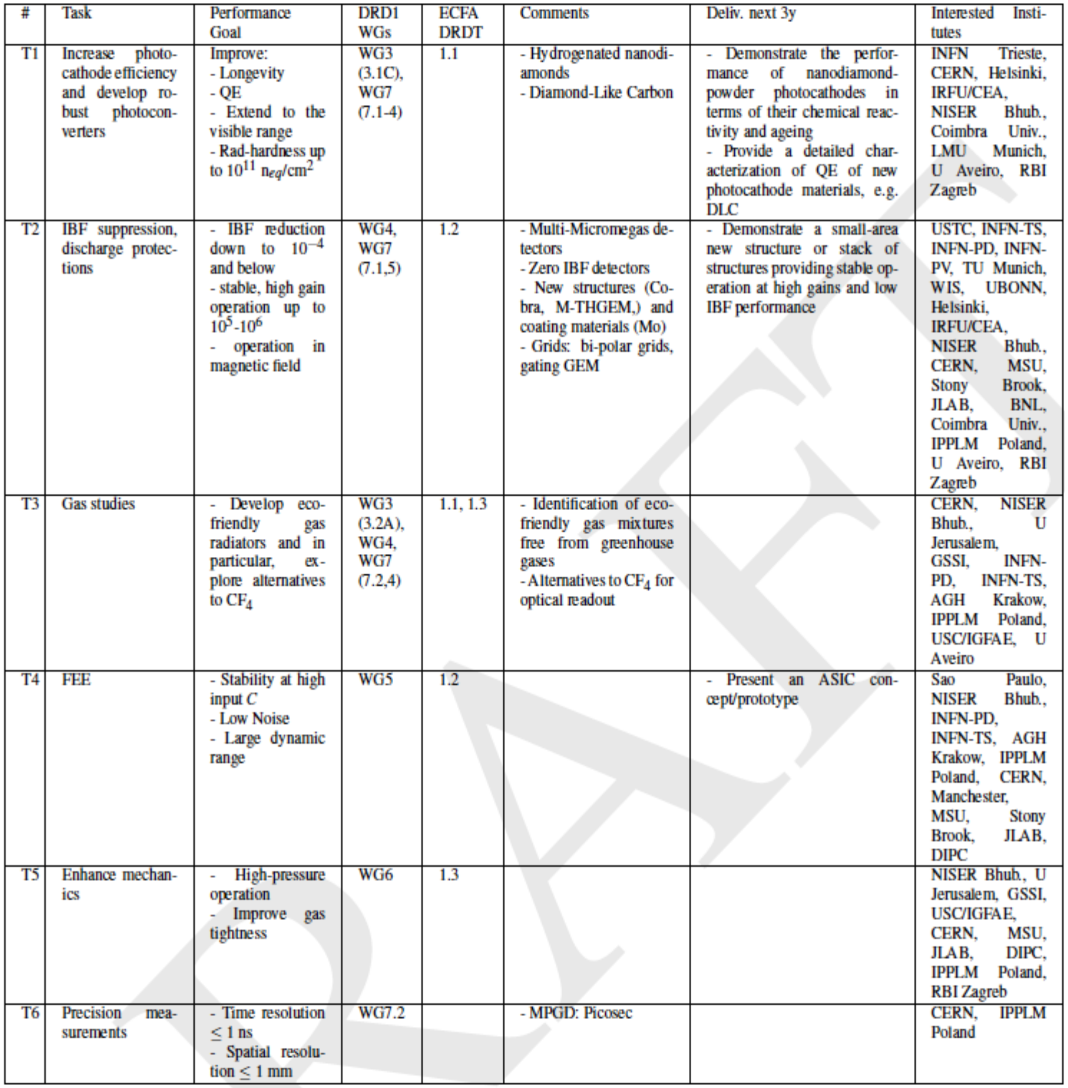
On-line version: `https://cernbox.cern.ch/s/BKQsu6oiuhPWDaa`

DRD1 Website: `https://drd1.web.cern.ch/`

Geneva, Switzerland
July 30, 2023

First draft submitted to DRDC on July 31st 2023

DRD1 Work Package: example Photon detectors (WP6)



#	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

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.

Conclusion and remarks

Technological Advancements

in innovative materials, new architectures and cutting-edge technical solutions have ushered in a new era in the operational capabilities of gas detector, enabling these detectors to work under increasingly demanding conditions.

- ✓ These remarkable developments stand to greatly benefit both upcoming and future experiments.

A strategic approach

is focused on knowledge-sharing, hybridization of technologies, combined features in the same detector (5D detector)

Success of Collaborative Efforts

the experience of RD51 has vividly demonstrated that collaborative endeavors yield success and pave the way for sustainable developments in our field.

DRD1 Collaboration

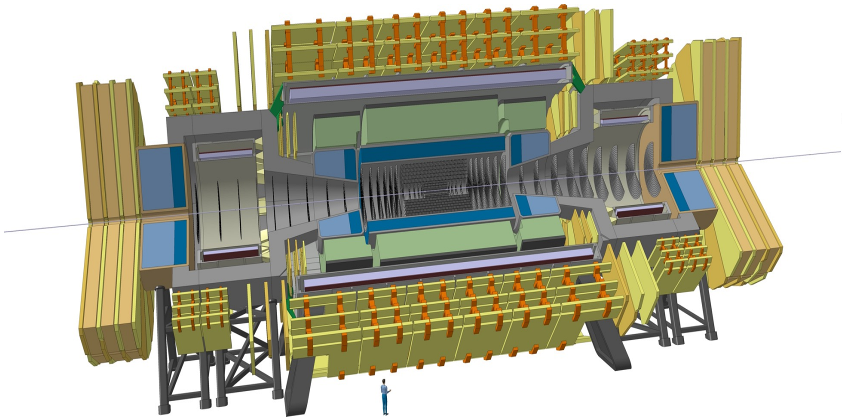
will unite groups engaged in diverse applications, leveraging various technologies and solutions.

➔ This presents a significant opportunity to advance our collective knowledge and capabilities.

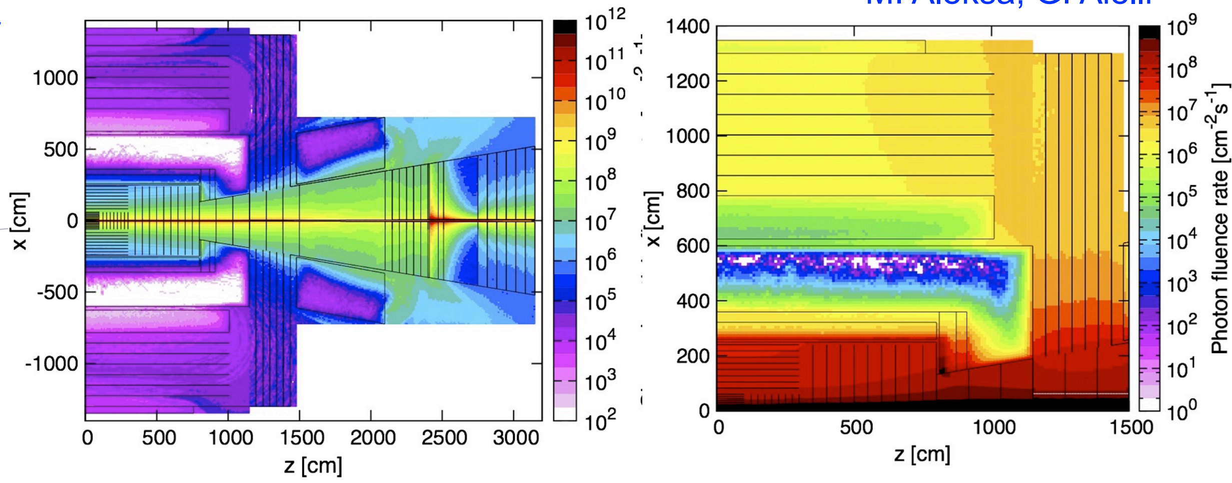
Additional slides

Muon system for FCC-hh

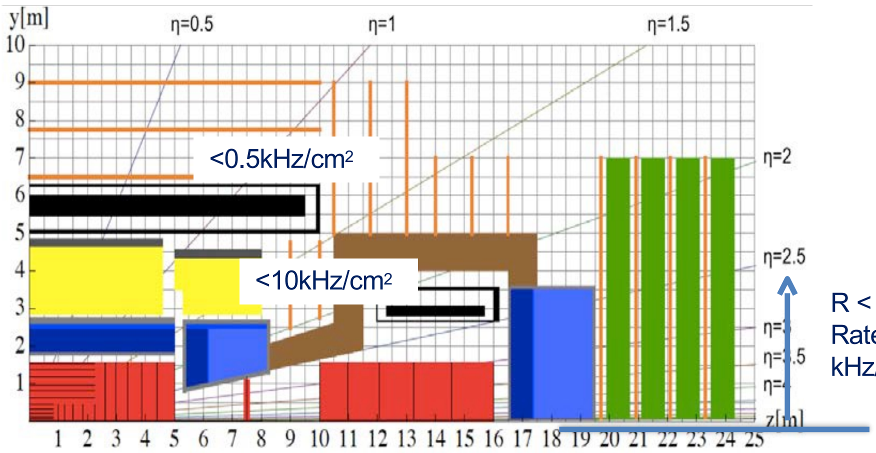
Muon System, tracking and trigger capabilities with resolution of 50 um, $\sigma_{p_T}/p_T \approx 5\%$ at 10TeV



M. Aleksa, G. Aielli



- 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 ~ 5×10^{4} $cm^{-2}s^{-1}$
- photon rates ~ $5\times10^{6-8}$ $cm^{-2}s^{-1}$
- 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

TPC 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**

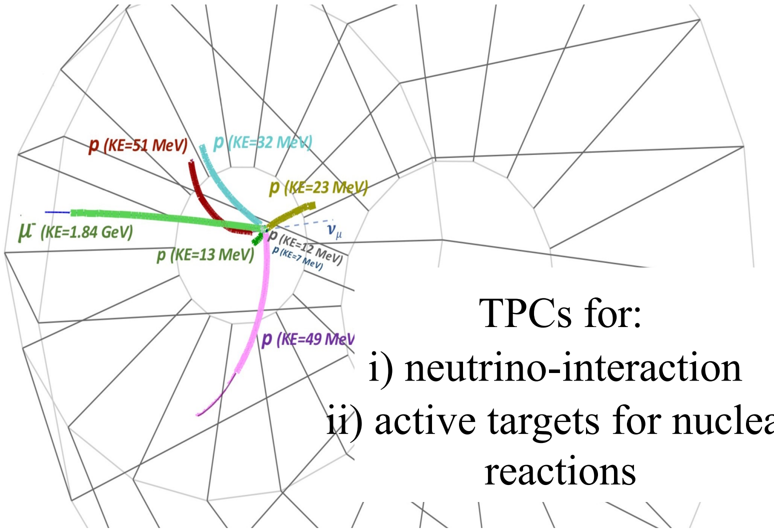
Direction of WIMP Flux

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)

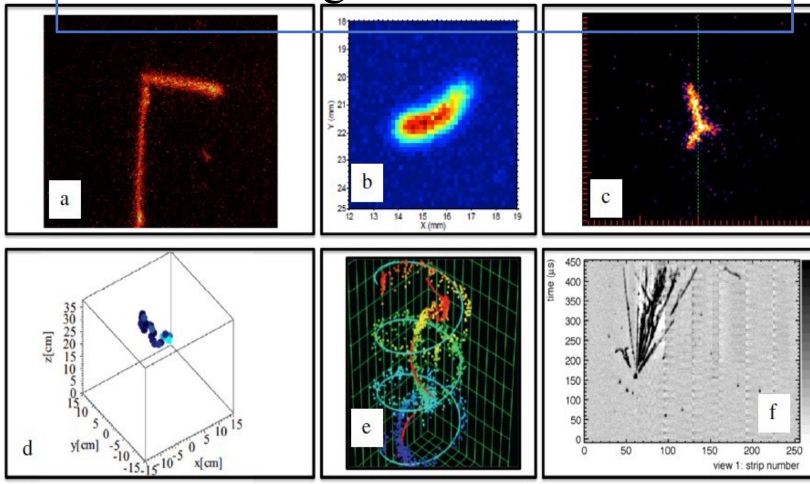
Particle Trackers for Neutrino Oscillation NDs

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

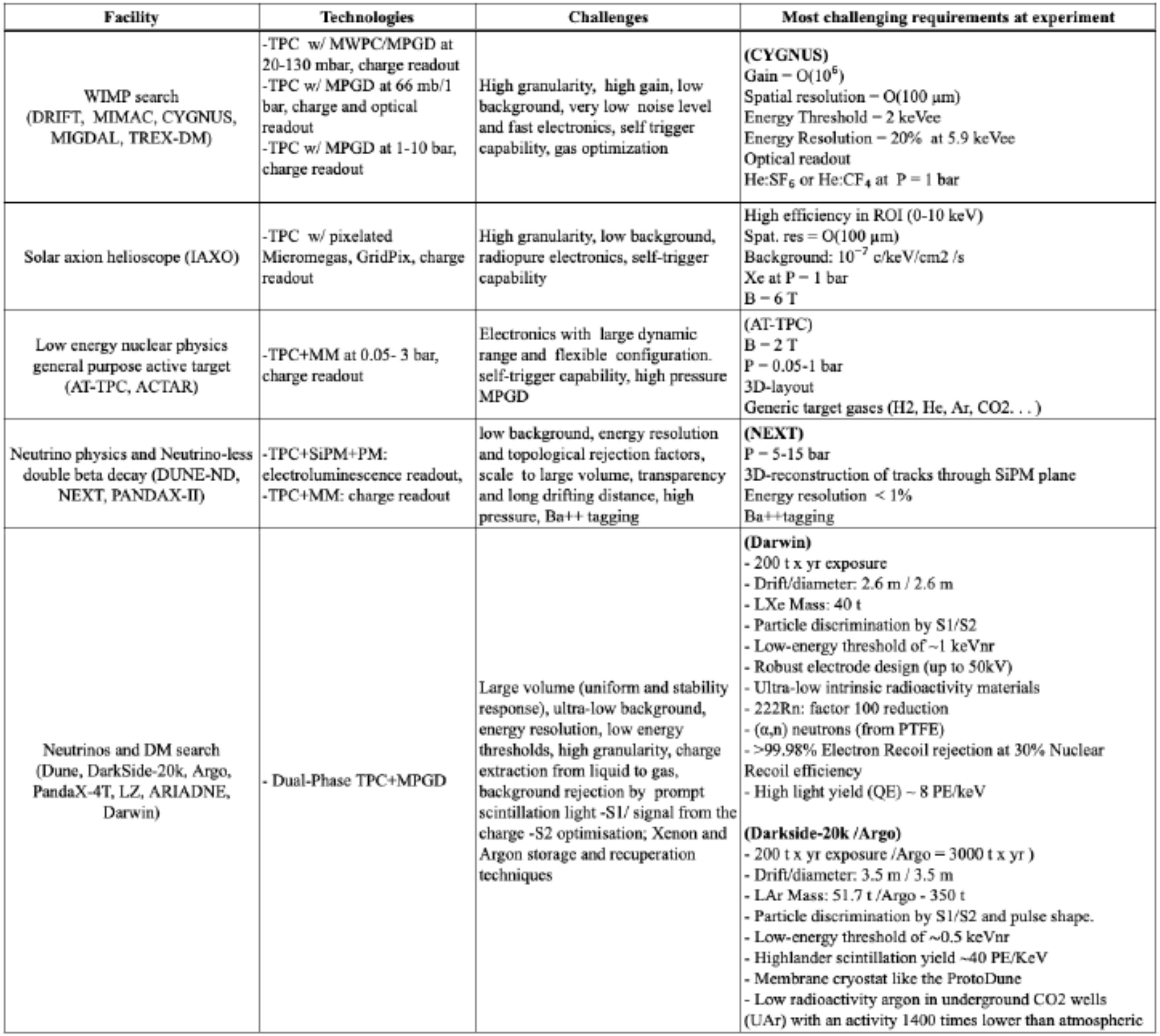


TPCs for:
i) neutrino-interaction
ii) active targets for nuclea
reactions

‘TPC == single reconstruction-tool’



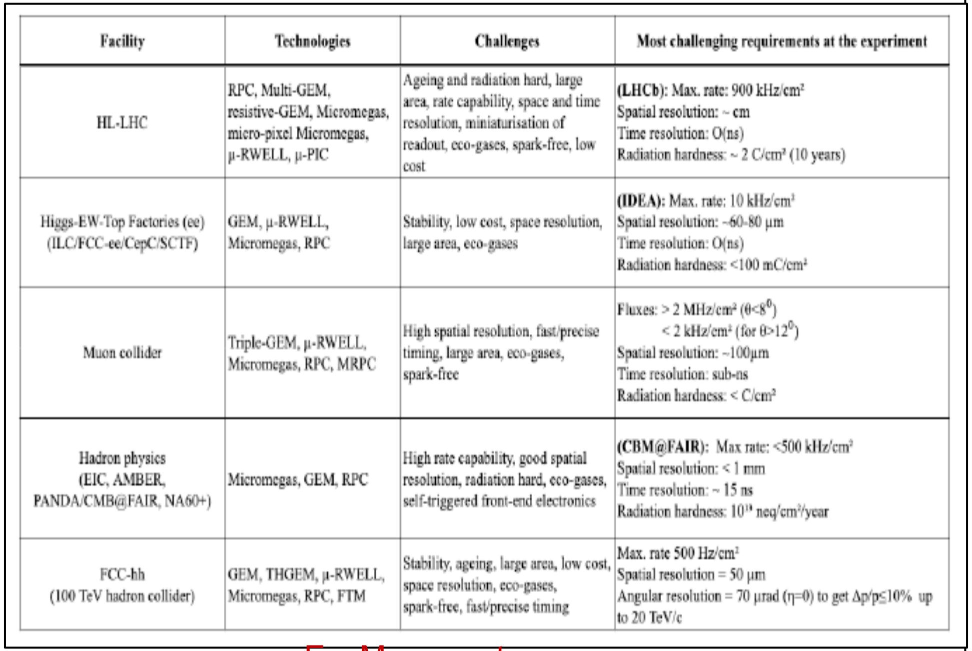
TPC as reaction/decay chambers



Facility	Technologies	Challenges	Most challenging requirements at experiment
WIMP search (DRIFT, MIMAC, CYGNUS, MIGDAL, TREX-DM)	-TPC w/ MWPC/MPGD at 20-130 mbar, charge readout -TPC w/ MPGD at 66 mb/1 bar, charge and optical readout -TPC w/ MPGD at 1-10 bar, charge readout	High granularity, high gain, low background, very low noise level and fast electronics, self trigger capability, gas optimization	**(CYGNUS)** Gain – O(10^6) Spatial resolution – O(100 μm) Energy Threshold – 2 keVee Energy Resolution – 20% at 5.9 keVee Optical readout He:SF_6 or He:CF_4 at P = 1 bar
Solar axion helioscope (IAXO)	-TPC w/ pixelated Micromegas, GridPix, charge readout	High granularity, low background, radiopure electronics, self-trigger capability	High efficiency in ROI (0-10 keV) Spat. res = O(100 μm) Background: 10^{-7} c/keV/cm2 /s Xe at P – 1 bar B – 6 T
Low energy nuclear physics general purpose active target (AT-TPC, ACTAR)	-TPC+MM at 0.05- 3 bar, charge readout	Electronics with large dynamic range and flexible configuration. self-trigger capability, high pressure MPGD	(AT-TPC) B – 2 T P – 0.05-1 bar 3D-layout Generic target gases (H2, He, Ar, CO2. . .)
Neutrino physics and Neutrino-less double beta decay (DUNE-ND, NEXT, PANDAX-II)	-TPC+SiPM+PM: electroluminescence readout, -TPC+MM: charge readout	low background, energy resolution and topological rejection factors, scale to large volume, transparency and long drifting distance, high pressure, Ba++ tagging	**(NEXT)** P – 5-15 bar 3D-reconstruction of tracks through SiPM plane Energy resolution < 1% Ba++tagging
Neutrinos and DM search (Dune, DarkSide-20k, Argo, PandaX-4T, LZ, ARIADNE, Darwin)	- Dual-Phase TPC+MPGD	Large volume (uniform and stability response), ultra-low background, energy resolution, low energy thresholds, high granularity, charge extraction from liquid to gas, background rejection by prompt scintillation light -S1/ signal from the charge -S2 optimisation; Xenon and Argon storage and recuperation techniques	**(Darwin)** - 200 t x yr exposure - Drift/diameter: 2.6 m / 2.6 m - LXe Mass: 40 t - Particle discrimination by S1/S2 - Low-energy threshold of ~1 keVnr - Robust electrode design (up to 50kV) - Ultra-low intrinsic radioactivity materials - 222Rn: factor 100 reduction - (α,n) neutrons (from PTFE) - >99.98% Electron Recoil rejection at 30% Nuclear Recoil efficiency - High light yield (QE) ~ 8 PE/keV **(Darkside-20k /Argo)** - 200 t x yr exposure /Argo = 3000 t x yr) - Drift/diameter: 3.5 m / 3.5 m - LAr Mass: 51.7 t /Argo - 350 t - Particle discrimination by S1/S2 and pulse shape. - Low-energy threshold of ~0.5 keVnr - Highlander scintillation yield ~40 PE/KeV - Membrane cryostat like the ProtoDune - Low radioactivity argon in underground CO2 wells (UAr) with an activity 1400 times lower than atmospheric

ECFA DETECTOR R&D ROADMAP CONTENT: TF1

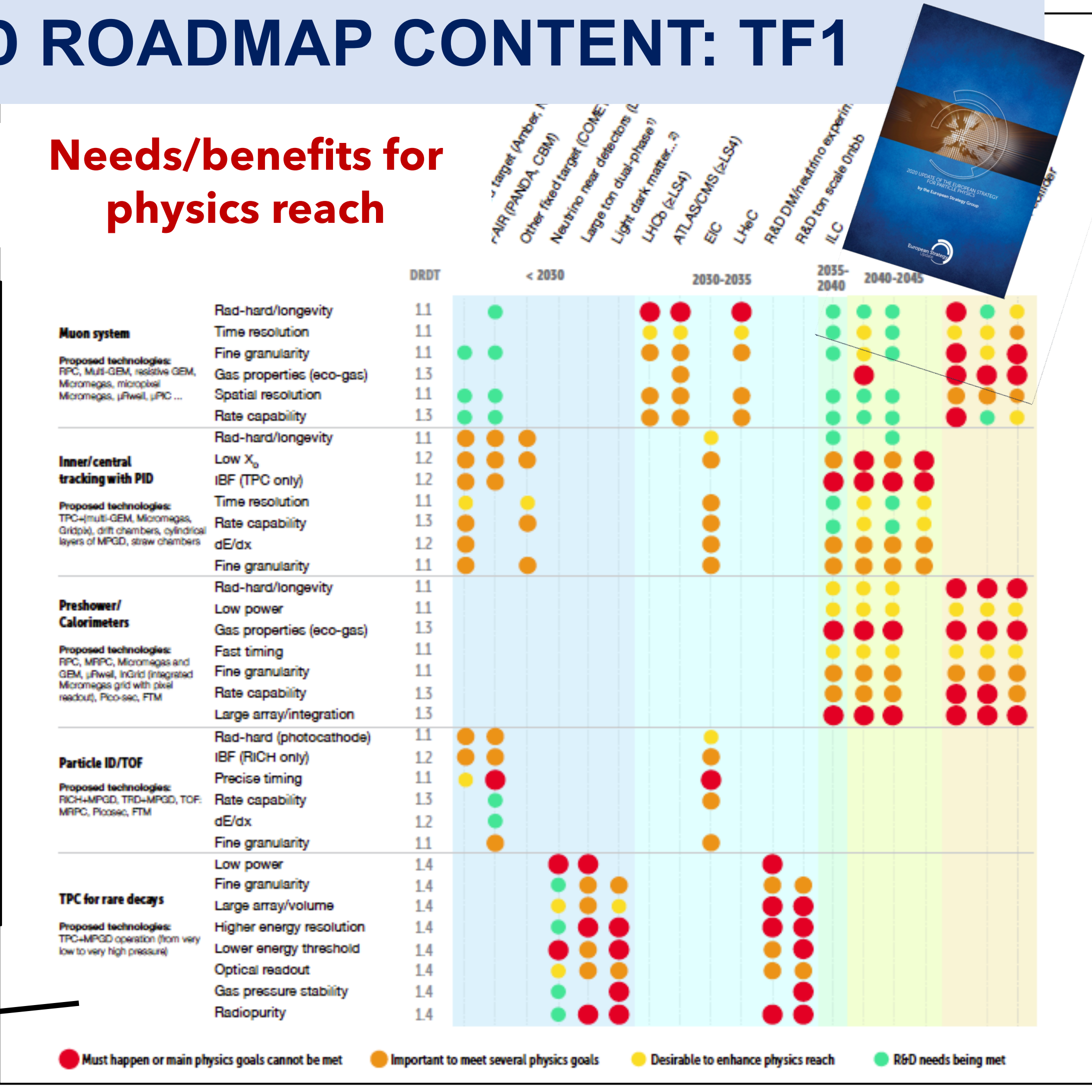
Performance targets and main drivers from facilities



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

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

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

From TF1 to DRD1: Implementation timeline

Q4-2022/Q1-2023

- Formation of the DRD1 proposal team
- Collection of interest from the institutes (survey)
- 1st Workshop and shaping the direction of RD.
- DRDC mandate reviewed and agreed with CERN management and EDP

Q2-2023

- **Writing the proposal** (scientific and organization) that includes conclusion and feedback from the workshop and survey
- Collect feedback by institutes in contact with their funding agencies about the best funding schema
- 2nd Community Workshop
- Mechanisms agreed with funding agencies for country specific DRD funding request.

Q3-2023

End July –submission of the proposal, including resource information:

- resources needed
- resources already available
- Interest of institutes/FA to contribute to specific tasks
- DRDC review (scientific, milestones, feasibility, financials)

Q4-2023

- Establishing continuation of existing RD51 projects and carrying resources
- DRD1 organization and scientific programs defined.
- Follow the review revisions and upon green light from DRDC, CERN research board approves the formation of the collaboration

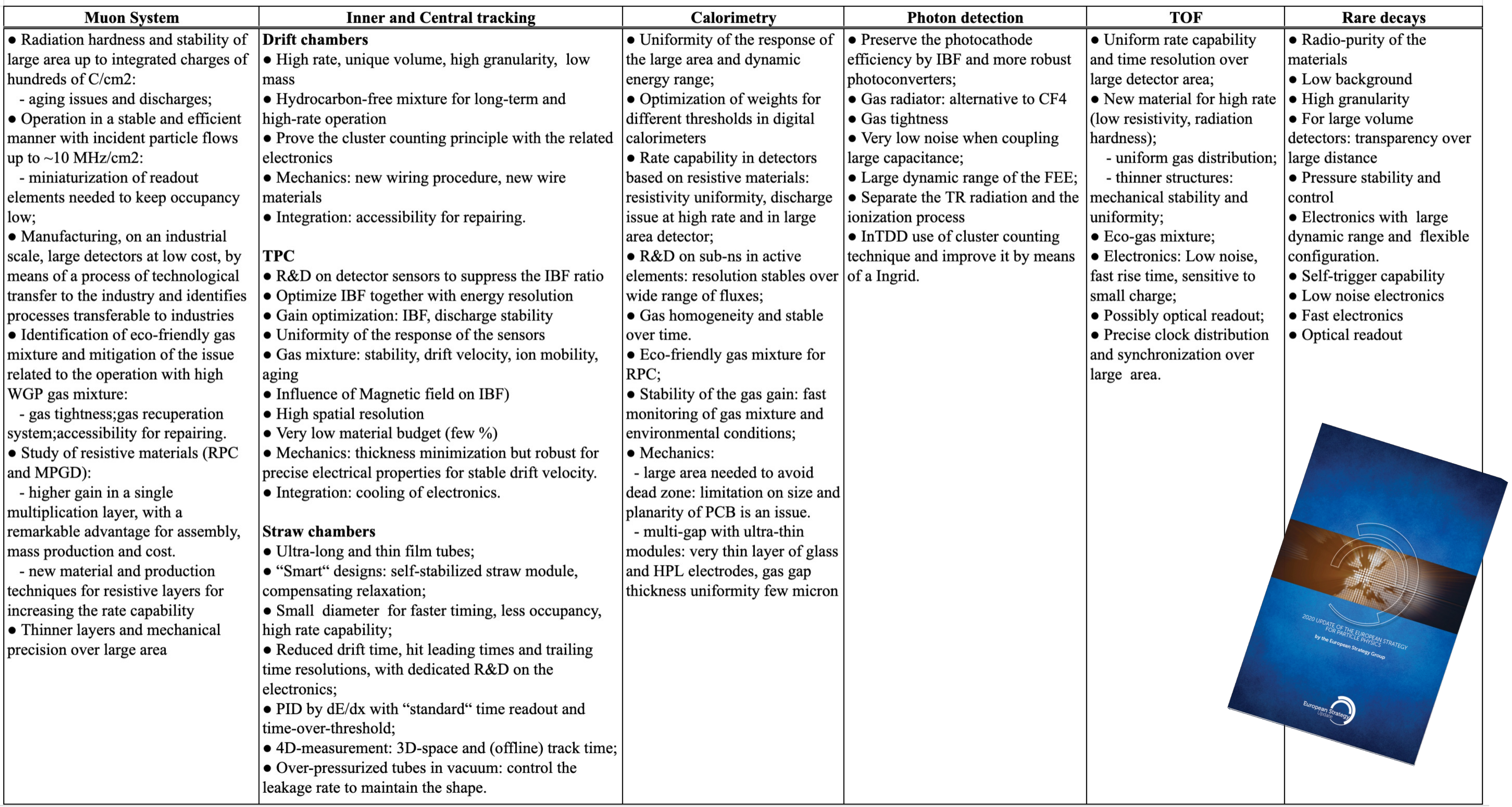
2024

- New structures operational and new R&D programmes underway
- Through 2024, collection of MoU signatures with defined contribution areas per institute.
- Start monitoring progress in organization

- Ramp up of new strategic funding and R&D activities 2024-2026

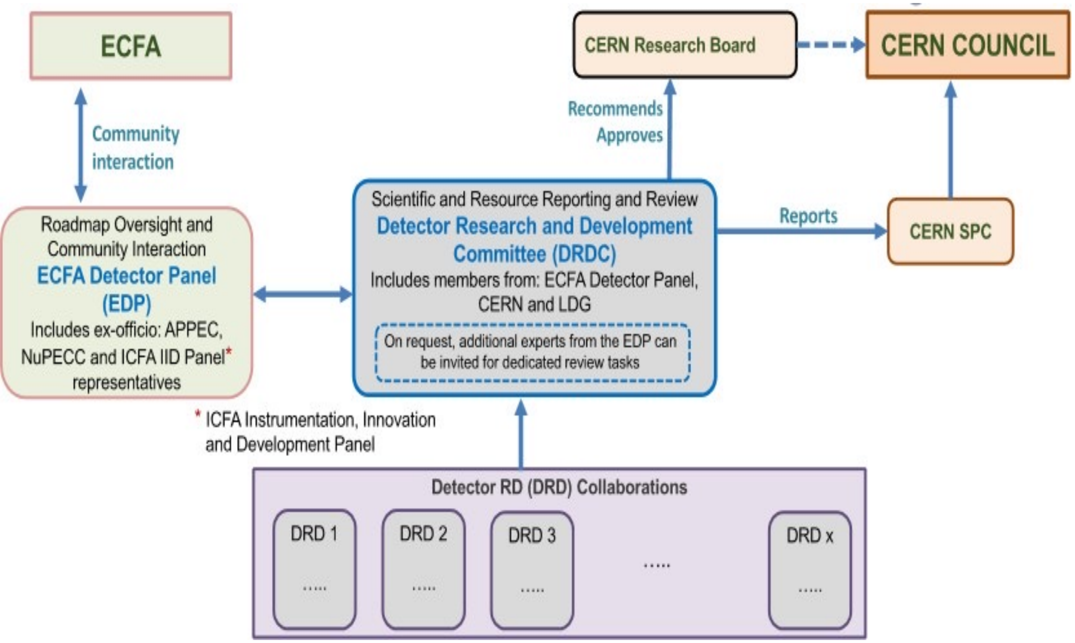
The wide family of gaseous detectors: applications

Summary of R&D Challenges for the 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

DRD approval process and review



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➔ 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