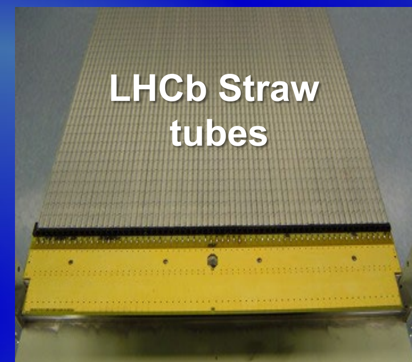


Gaseous Detectors R&D for FCC

Maxim Titov
CEA Saclay IRFU / CERN

Future Circular Collider Week (FCC), London, June 5-9, 2023

Gaseous Tracking / Muon Detection @ Future Colliders:

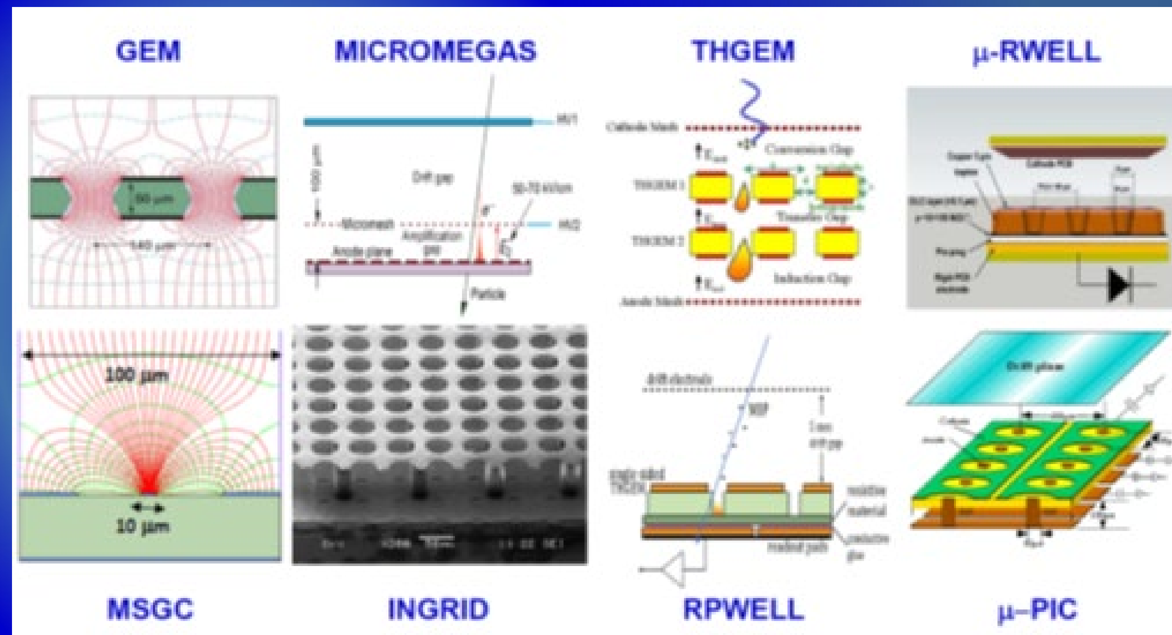
Drift Chamber → TPC → RPC → Micro-Pattern Gas Detectors

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

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

- ✓ 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
- ✓ Successful accomplishment of LHC upgrades will help to disseminate MPGD technologies even wider

RD51 extension (2019-2023): arXiv: 1806.09955



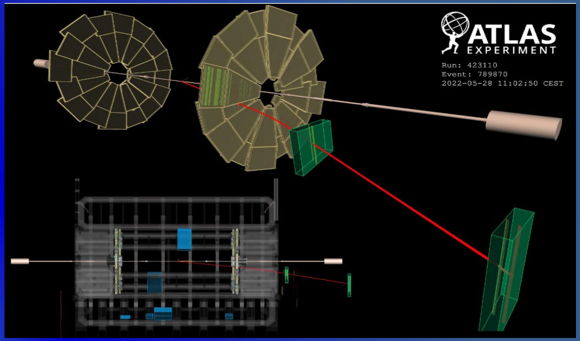
HL-LHC Upgrades: Tracking (ALICE TPC/GEM); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;

Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, particle rates are comparable with HL-LHC)
Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (many gas det. are OK)

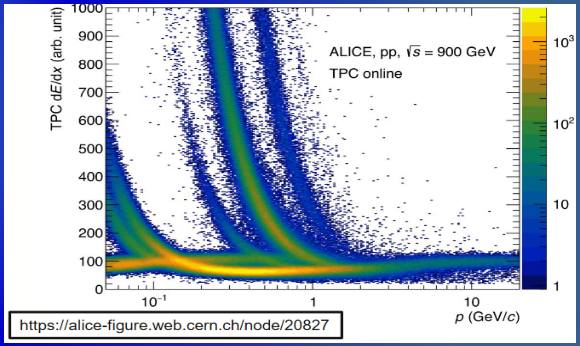
Future Election-Ion Collider: Tracking (GEM, μWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)

CERN Detector Seminars in 2022: LS2 Upgrades

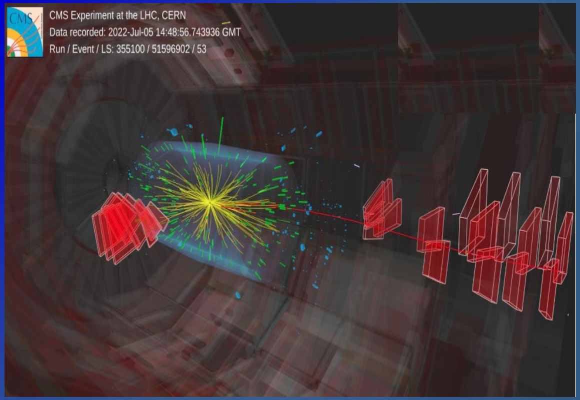
Major MPGDs developments for ATLAS, CMS, ALICE upgrades, towards establishing technology goals and technical requirements, and addressing engineering and integration challenges … and first results from Run 3 !!!



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



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



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

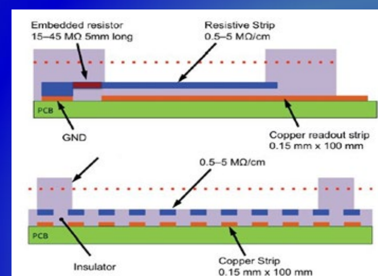
All three major LHC upgrades, incorporating MPGDs, started their R&D in close contact with RD51, using dedicated setups at GDD-RD51 Laboratory

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

Resistive MM for ATLAS NSW Muon Upgrade:

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

- Add a layer of resistive strips above the readout strips
- Spark neutralization/suppression (sparks still occur, but become inoffensive)



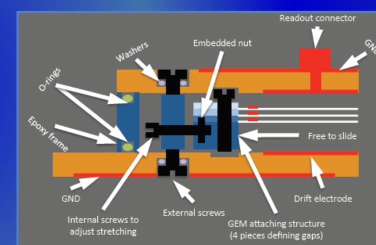
Still, main issue encountered: HV unstability
==> found to be correlated to low resistance of resistive strip anode
==> applied solutions + passivation in order to deactivate the region where R<0.8 MΩ

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

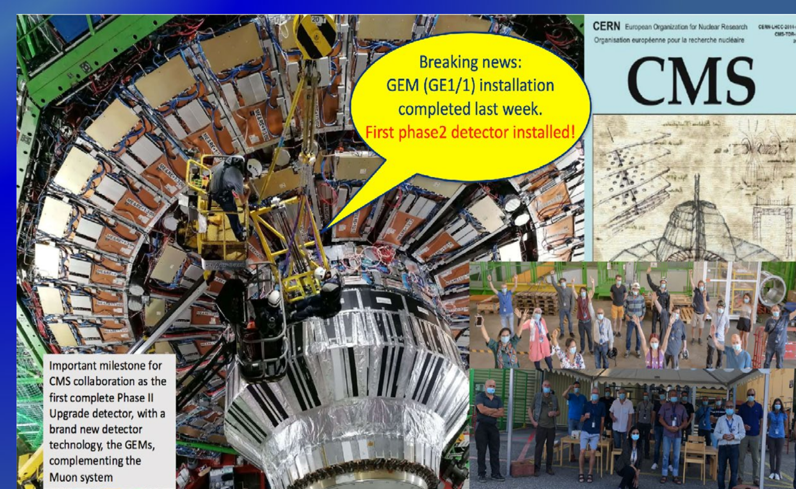
GEMs for CMS Muon System Upgrade:

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

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



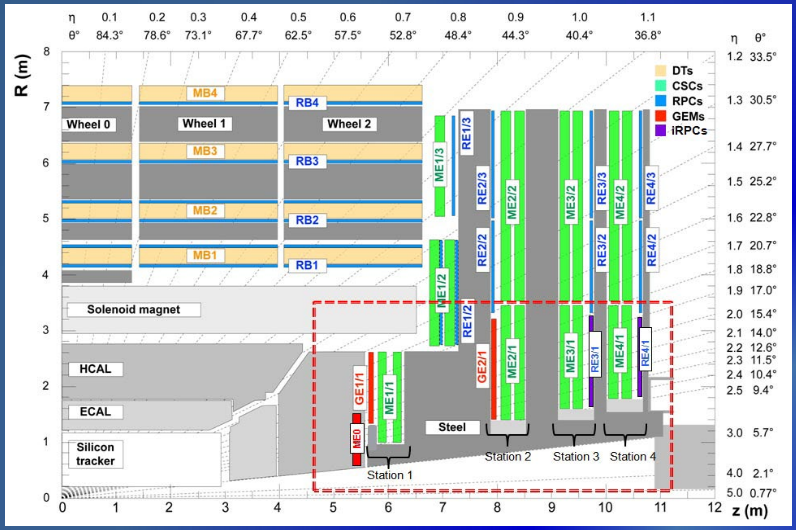
September 2020: 144 GEM chambers installed



Gaseous Detectors @ CMS, ALICE, LHCb Upgrades

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

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



GE21 Detector System

- 72 chambers arranged in 2 layers installed
- On-chamber and off-chamber
  - 4 triple GEM modules per chamber
- 20^0 Chambers, layout similar to GE1/1, but covering much larger surface. (1.62<h<2.43)
- hit rate < 2 kHz/cm^2 (GE1/1 was up to 5 kHz/cm^2)

ME0 Detector System

- 36 Stacks 6 layers each
- 20^0 Stacks, Module Size comparable with GE1/1 chamber but covering high eta region (2<h<2.8)
- Background ~ 10^2 higher that GE2/1, very demanding from performance point of view

A. Colaleo

September 2020: 144 GEM GE1/1 chambers installed

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

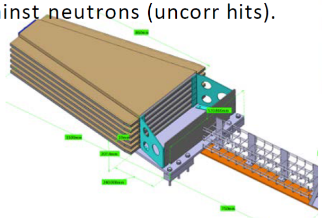
Triple GEM for HL-LHC in CMS: ME0

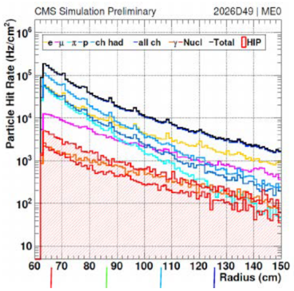
High granularity and spatial segmentation for for efficient matching of muon stubs to the offline pixel tracks.

Multi-layered structure to discriminate muon against neutrons (uncorr hits).

Detector requirements

- Rate-Capability: up to 150kHz/cm^2
- Ageing: 7.9 C/cm^2 integrated charge in 10 yrs





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

Discharge and x-talk mitigation strategy

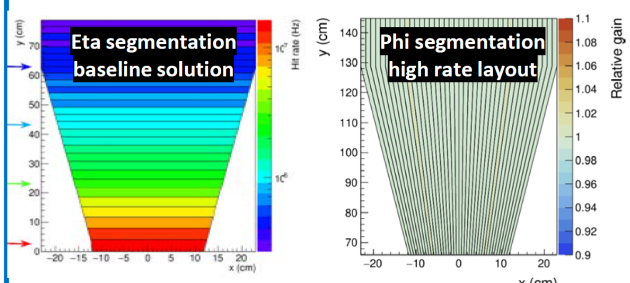
GEM Foils Stack Design changes:

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

Aging test tests

No aging observed anywhere in Ar:CO_2 up to 1.5 C/cm^2 => 7,9 C/cm2 expected by 2023

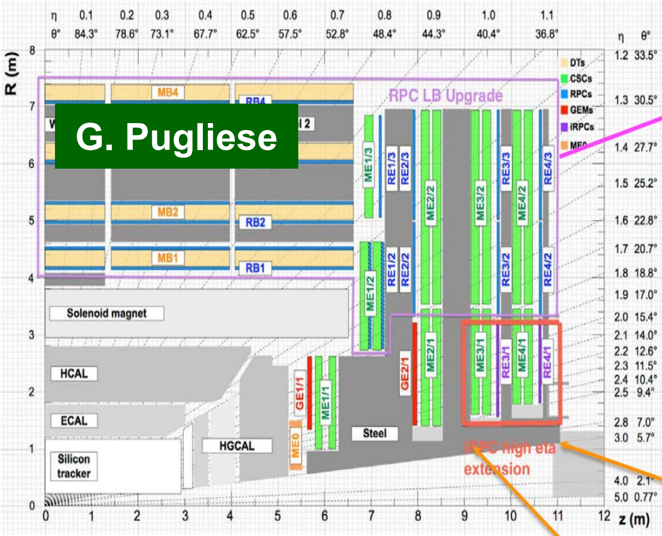
Optimization of GEM foil layout for high rates



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

CMS RPC Upgrade Project for HL-LHC

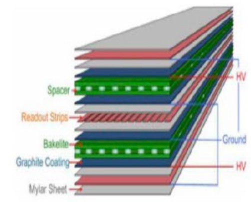
G. Pugliese



New LinkSystem (off-detector electronics):

- Increase readout frequency from 25 ns → 1.56 ns

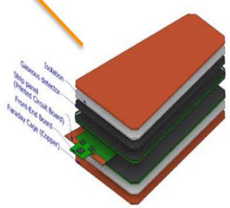
No changes in the RPC detectors:



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

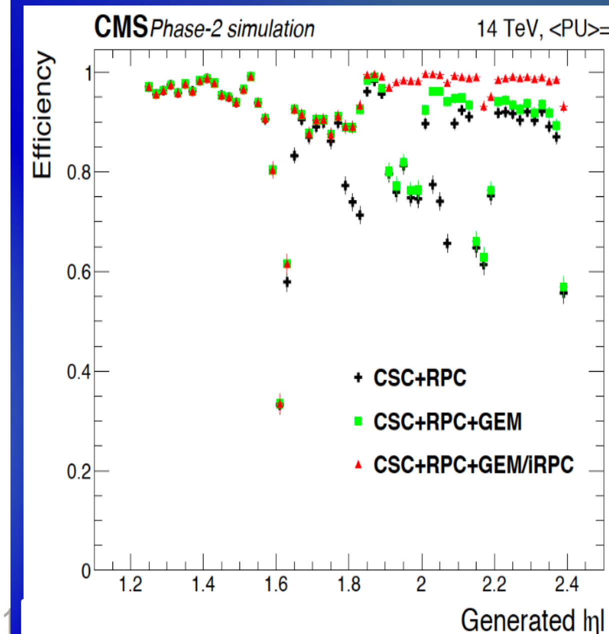
Improved RPCs:

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



	iRPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}	1 - 6 x 10^{10}
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions

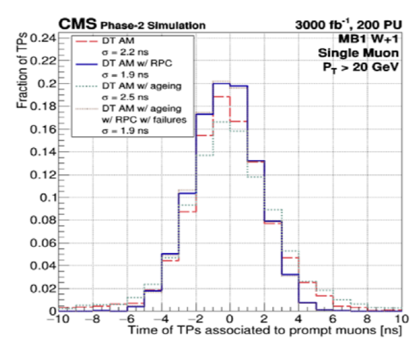
iRPC extended |η| coverage increases forward muon efficiency for 4 fired muon stations

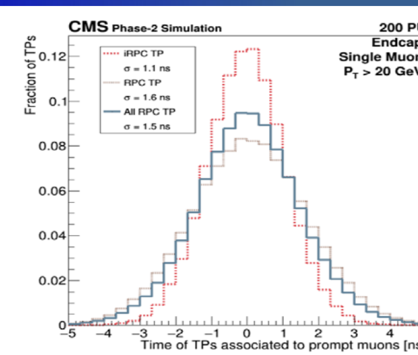


Effect of the improved time resolution of the RPC system in Phase 2:

Barrel Muon Track Finder (BMTF): it uses DT and RPC trigger primitives (TP) to reconstruct segments merged to obtain a muon candidate. RPC improves TP time resolution by ~15(30)% without(with) DT aging.

Endcap Muon Track Finder (BMTF): RPC is the only muon detector providing timing with more granularity than a bunch-crossing





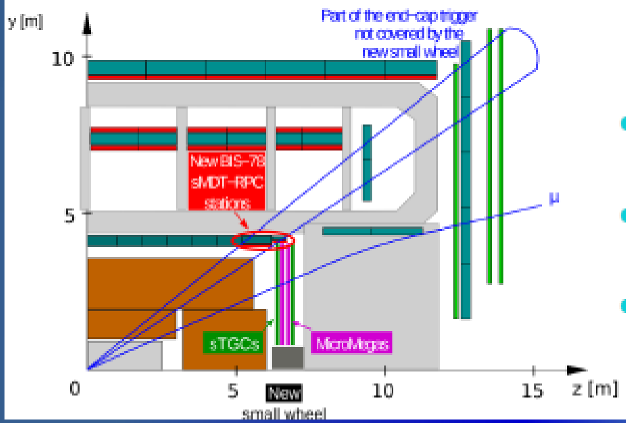
ATLAS Muon System Upgrade @ HL-LHC

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
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
ATLAS MUON UPGRADE (proposed, not approvedt) CERN AFTER LS3	Hadron Collider (Tracking/Triggering) (2.7 ≤|h| ≤ 4.0)	Forward region: Res MM, μWELL, μPIC	Total area: ~ 5 layers x1 m^2 Single unit detect: 0.1 m^2	**Max. rate**: 10 MHz/cm^2 **Spatial res.:** ~200 μm **Time res.:** ~ 5 ns **Rad. Hard.:** ~ 10 C/cm^2	Hit rates falls rapidly with the distance from the beam axis. Given parameters are for extreme conditions at 25 cm from the beam. Miniaturization of readout elements needed there to keep occupancy low

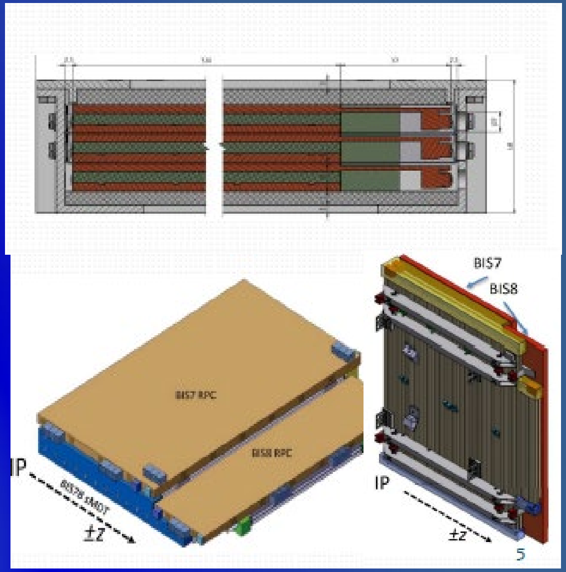
ATLAS RPC Upgrade Project for HL-LHC Upgrade

✓ **BIS78 Upgrade – Pilot Project (LS2):**

G. Aielli



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



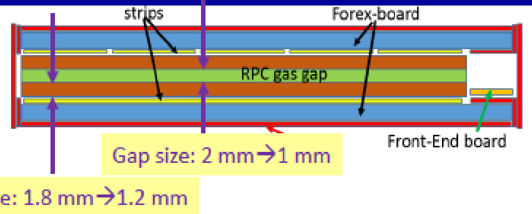
✓ **BI RPC Upgrade (LS3):**

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

New generation of RPC for BI

The challenge is to build a new generation of RPCs with higher rate capability and longevity.

- Higher rate capability: → kHz/cm^2
- Longer longevity: >10 years @ HL-LHC
- Higher spatial resolution: <1 cm
- Higher time resolution: ~ 0.5 ns



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

Y. Sun

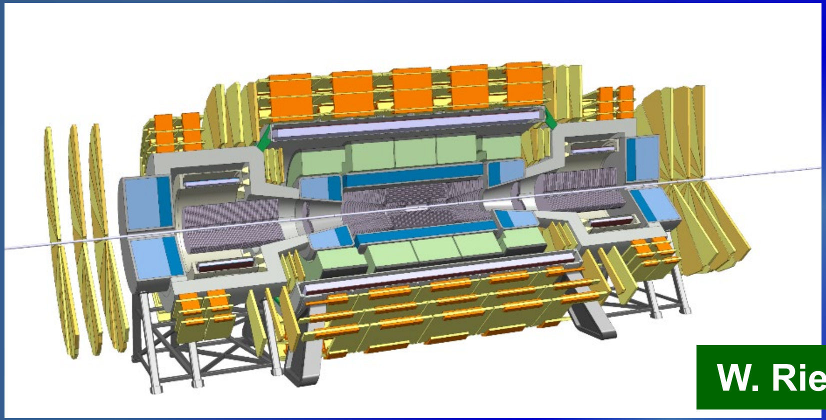
Muon Systems at Future Colliders (FCC, LHeC, Muon)

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

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

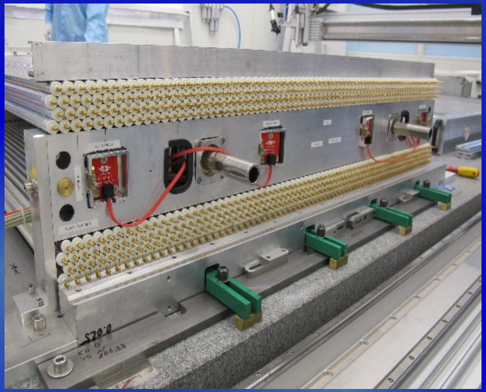
Muon System for the FCC-hh Collider

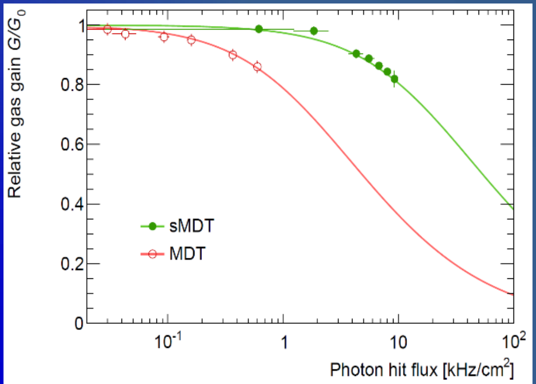
Barrel Muon system (2 layers) : 2000 m^2 total
Endcap Muon System (2 layers): 500 m^2 total
Forward Muon System: (4 layers): 320 m^2 total



W. Riegler

ATLAS MDT Drift Tubes:

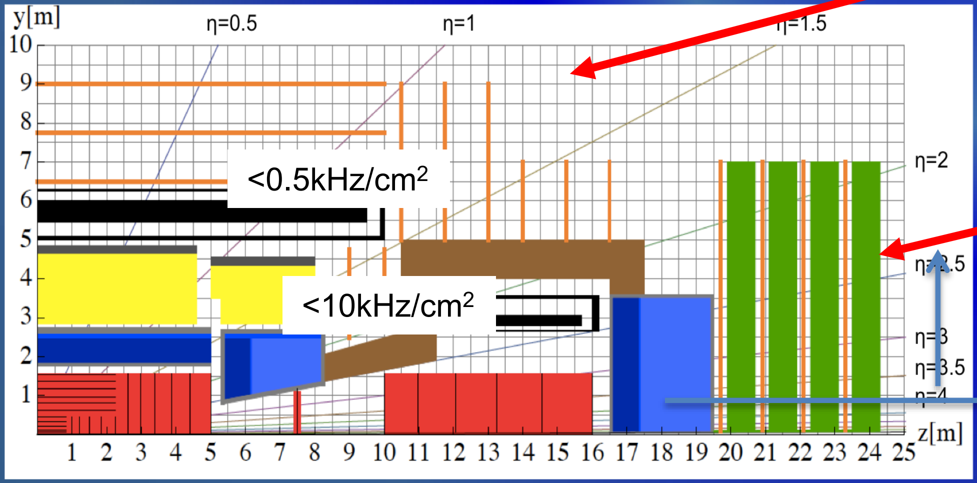




ATLAS Muon System HL-LHC: (kHz/cm²):

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

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



R > 1m : rate<500 kHz/cm²

LHCb Muon System (MWPC):

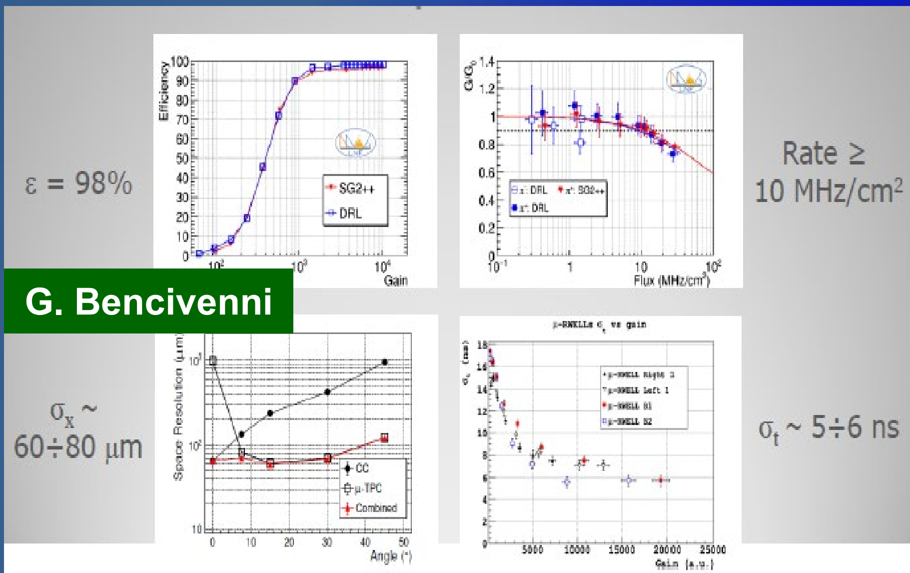
Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} $cm^{-2}s^{-1}$ at a collision energy of 14 TeV. The values are averages, in kHz/cm^2, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination.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

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

Forward region (r < 1 m) → more R&D would be needed

μ-RWELL for Preshower / Muon System @ FCC - ee

μ-RWELL Performance:



Technology transfer with ELTOS

DLC sputtering with new INFN-CERN machine @ CERN

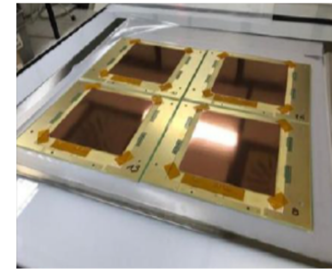
Step 1: producing μ-RWELL_PCB
- with top patterned (pad/strip)
- without bottom patterned

Step 2: DLC patterning
- in ELTOS with BRUSHING-machine

Step 3: DLC foil gluing on PCB
- double 106-prepreg (~2x50 μm thick) (already used in ELTOS)
- pre-smoothing + 106-prepreg (~50 μm thick)
- single 1080-prepreg (~75 μm thick)

Step 4: top copper patterning

Step 5: Kapton etching on small PCB



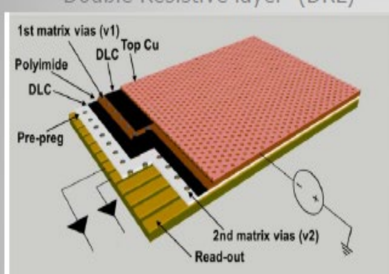
Finalization

Detector @ CERN for final preparation

μ-RWELL High-Rate Layout for LHCb Upgrade:

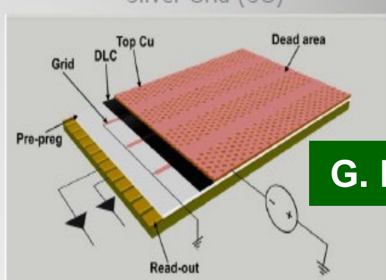
The purpose of these HR versions is to reduce the distance to be "travelled" by the charge towards the ground

Double Resistive layer (DRL)



- 3-D grounding
- Double DLC layers connected through matrices of conductive vias to the readout electrodes (density 1/cm2)

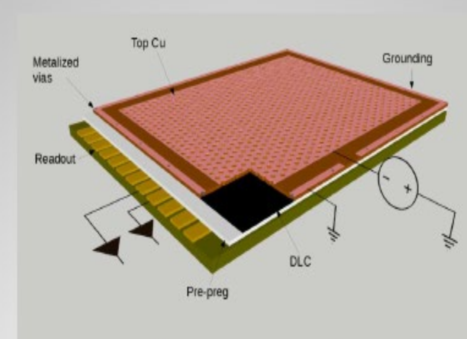
Silver Grid (SG)



- 2-D grounding
- Single DLC layer grounded by means conductive strip lines realized on the DLC layer (density 1/cm)

G. Bencivenni

μ-RWELL Low-Rate Layout for FCC-ee / CePC:



Single Resistive Layer (SRL)

- 2-D current evacuation scheme based on a single resistive layer
- conductive grounding line all around the perimeter of the active area
- Limitation for large area: the signal amplitude depends on the particle incident point → limited rate capability - O(10kHz/cm²)

Towards Large Area in 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

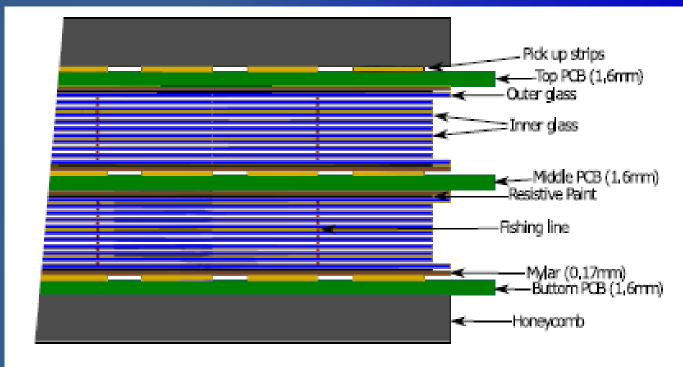
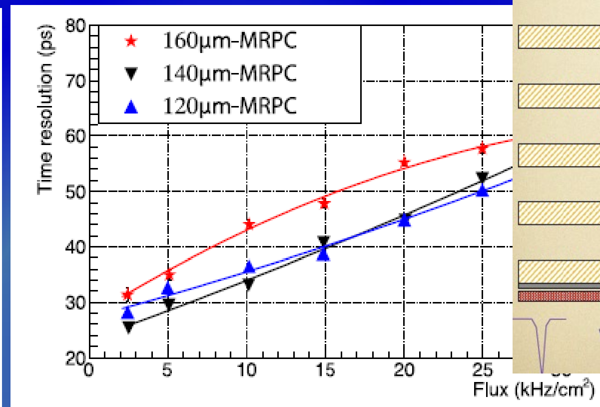
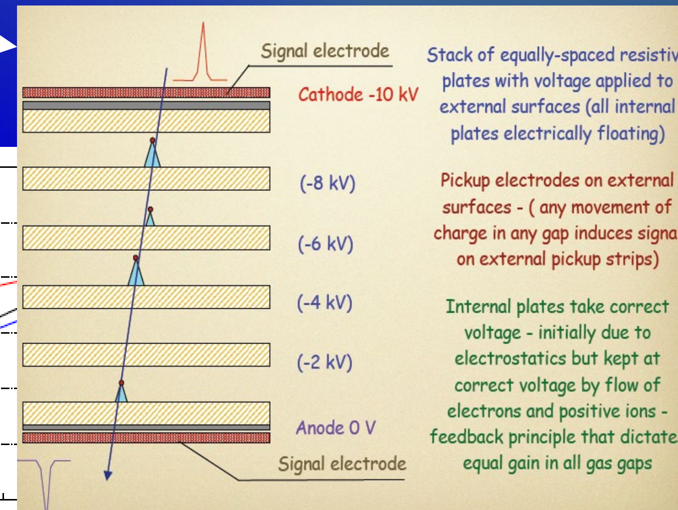


Fig. 1. Cross section of the double stack 20-gap MRPC.



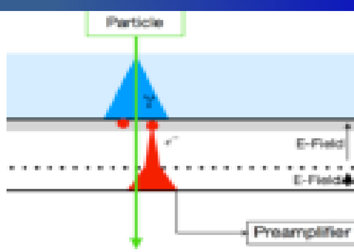


Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

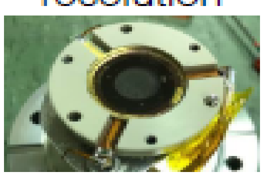
PICOSEC Micromegas

σ ~ 25 ps timing resolution (per track)

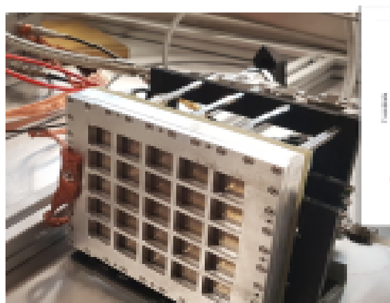
Cherenkov radiator + Photocathode + Micromegas

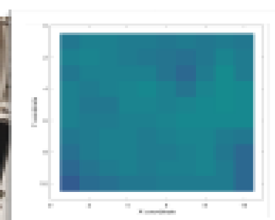


24ps timing resolution



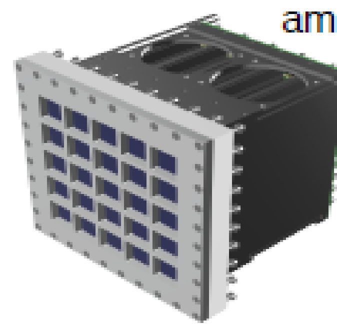
Tested in RD51 testbeam July 2021

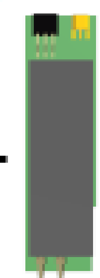




Planarity < 10µm

Custom pre-amp cards





Single pad (2016) ⌀1 cm

10x10 module ▫ 1 cm

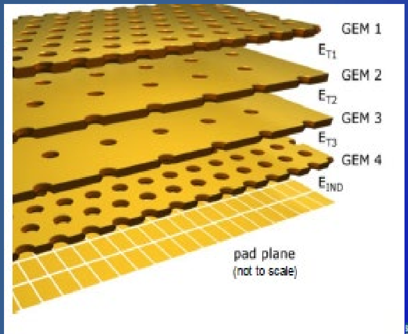
https://indico.cern.ch/event/1040996/contributions/4398412/attachments/2265036/3845651/PICOSEC-update-final.pdf

Gaseous Tracking Systems @ Future Colliders

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ILC TPC DETECTOR: STARTt: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm² (pixels)	**Max. rate**: < 1 kHz **Spatial res.:** <150μm **Time res.:** ~ 15 ns **dE/dx:** 5 %	Si + TPC Momentum resolution : dp/p < $9*10^{-5}$ 1/GeV Power-pulsing
CEPC TPC DETECTOR START: > 2030	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 2x10 m^2 Single unit detect: up to 0.04 m^2	**Max.rate**:>100 kHz/cm^2 **Spatial res.:** ~100μm **Time res.:** ~ 100 ns **dE/dx:** <5%	- Higgs run - Z pole run - Continues readout - Low IBF and dE/dx
FCC-ee and/or CEPC IDEA CENTRAL TRACKER START: >2030	e+e- Collider Tracking/ Triggering	He based Drift Chamber	Total volume: 50 m^3 Single unit detect: (12 m^2 X 4 m)	**Max. rate:** < 25 kHz/cm^2 **Spatial res.:** <100 μm **Time res.:** 1 ns **Rad. Hard.:** NA	Particle sepration with cluster counting at 2% level
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Main Tracker	Drift Chamber	Total volume: ~ 3.6 m^3	**Max. rate**: 1 kHz/cm^2 **Spatial res.:** ~100 μm **Time res.:** ~ 100 ns **Rad. Hard.:** ~ 1 C/cm	
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Inner Tracker	Inner Tracker / (cylindrical μRWELL, or TPC / MPDG read.	Total area: ~ 2 - 4 m^2 Single unit detect: 0.5 m^2	**Max. rate**: 50-100 kHz/cm^2 **Spatial res.:** ~<100 μm **Time res.:** ~ 5 -10 ns **Rad. Hard.:** ~ 0.1-1 C/cm^2	Challenging mechanics & mat. budget < 1% X0
ELECTRON-ION COLLIDER (EIC) START: > 2025	Electron-Ion Collider Tracking	Barrel: cylindrical MM, μRWELL Endcap: GEM, MM, μRWELL	Total area: ~ 25 m^2	Luminosity (e-p): 10^{33} **Spatial res.:** ~ 50- 100 um **Max. rate**: ~ kHz/cm^2	Barrel technical challenges: low mass, large area Endcap: moderate technical challenges

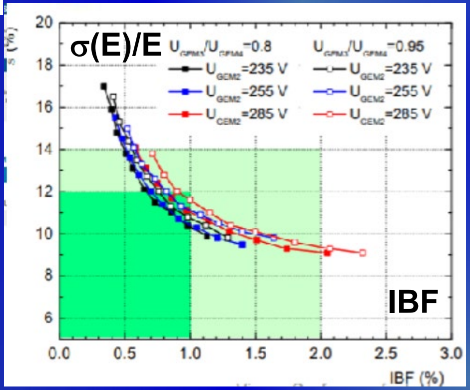
TPC with MPGD Readout for ALICE Upgrade and ILC

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

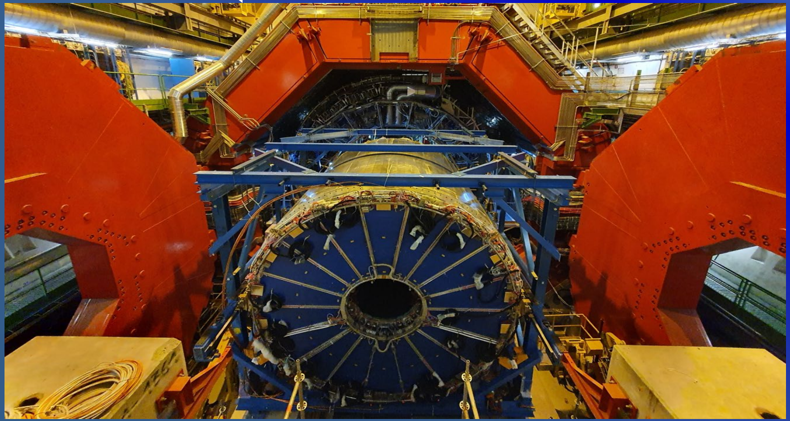


- Upgrade for continuous TPC readout @ 50 kHz Pb-Pb collisions

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



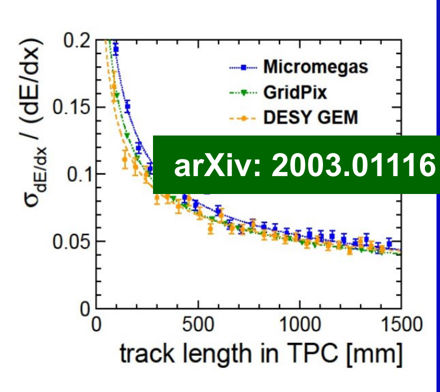
TPC reinstallation in the ALICE cavern (August 2020)

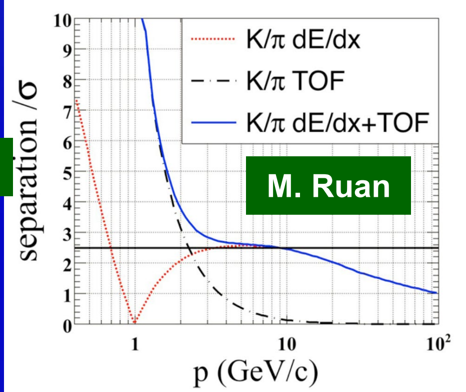


ILC –TPC with MPGD-based Readout

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

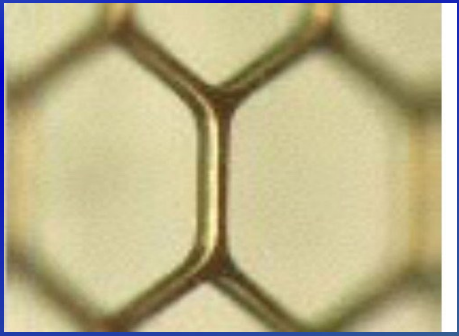
If dE/dx combined with ToF using SiECAL, P < 10GeV region for pion-K separation covered

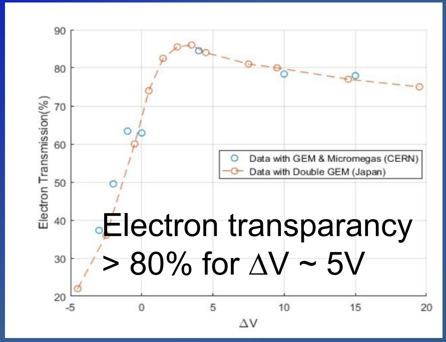




ILC: gating scheme, based on large-aperture GEM

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



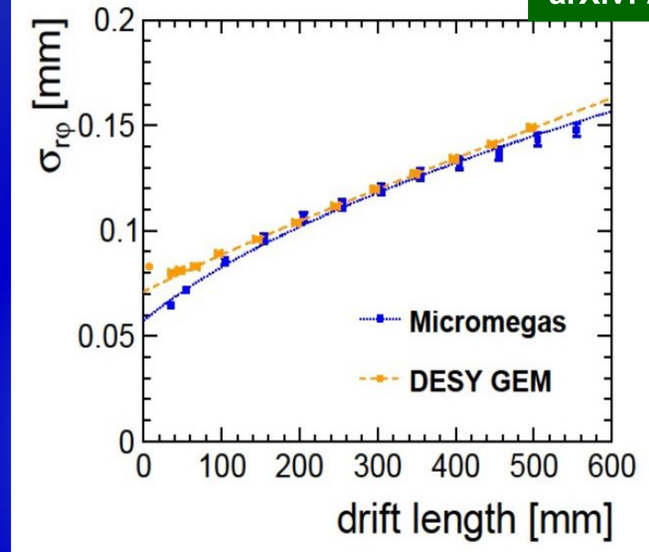


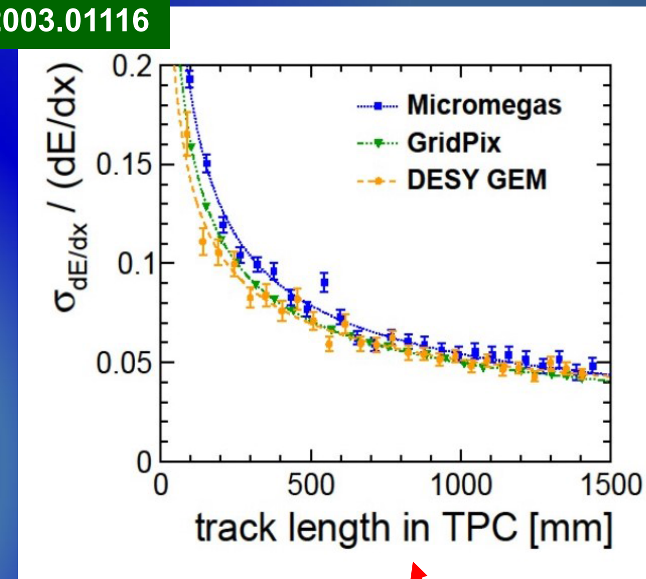
ILC TPC Performance: Technology Comparison

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

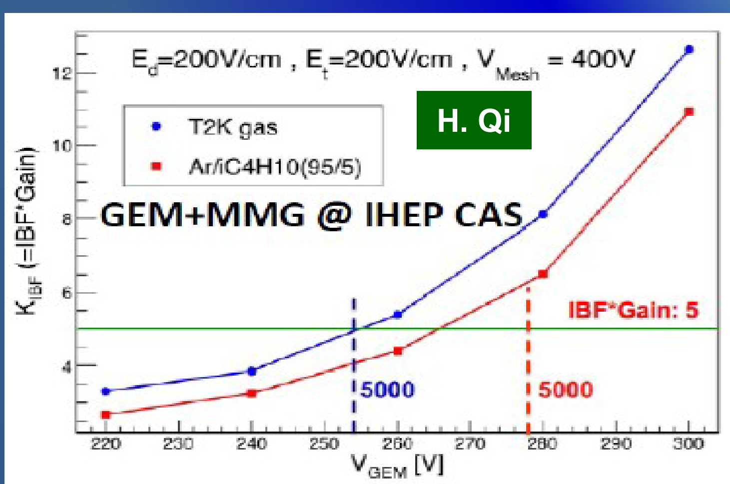
- ✓ GEM: ~ 4-6 mm^2 pads & sufficient diffusion in multi-GEM structure
- ✓ MM: 20 mm^2 pads & charge spreading using resistive-anode readout
- ✓ Gridpix: 55x55 μm^2 pixels with digital readout

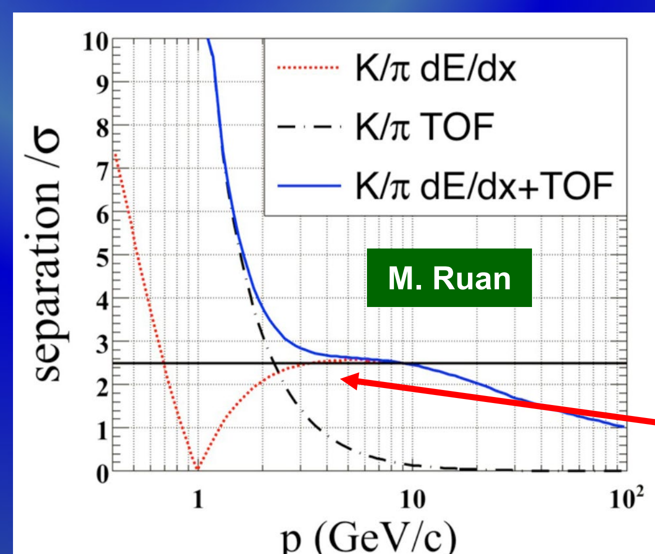
arXiv: 2003.01116





Micromegas + GEM studies for CEPC / FCC-ee to minimize ion backflow (gating is not possible)



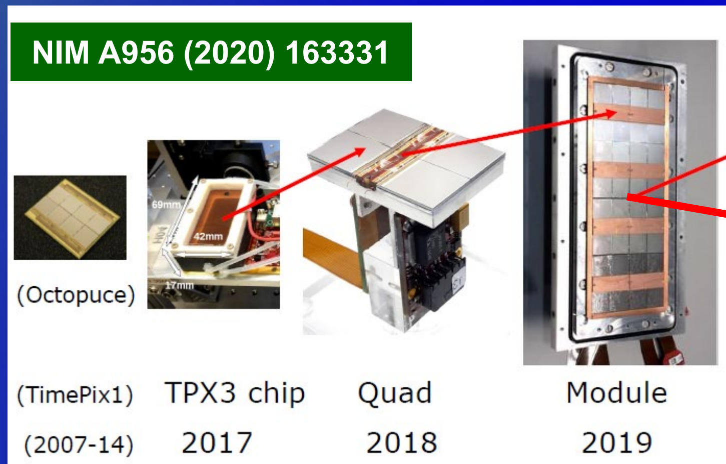


dE/dx ~ <4 % can be achieved with Gridpix (cluster-counting)

Added value of TIME information for ILC: dE/dx combined with ToF (SiW-ECAL) for K-PID

Towards Large-Scale Pixel "GridPix" TPC

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

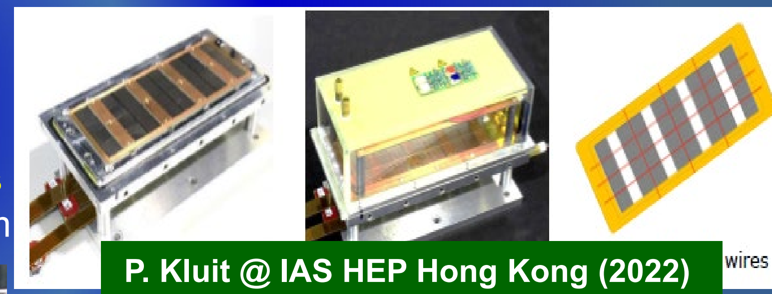


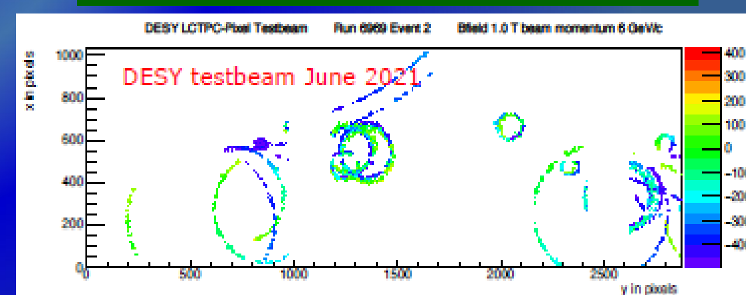
A PIXEL TPC IS REALISTIC!

Physics properties of pixel TPC:

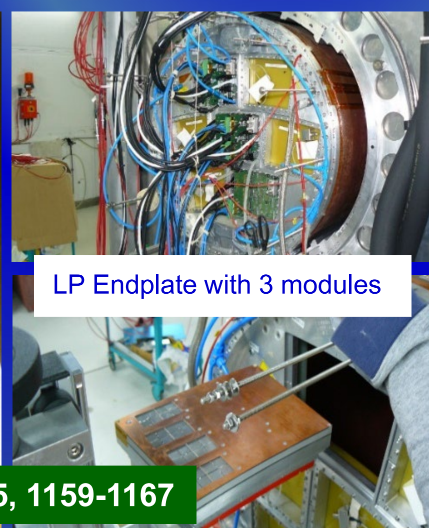
- Improved dE/dx by cluster counting
- Improved meas.of low angle tracks
- Excellent double track seperation
- Lower occupancy @ high rates
- Fully digital read out (TOT)

Quad board (Timepix3) as a building block
→ 8-quad detector (32 GridpPixs) with a field cage at test-beam @DESY in June 2021:





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



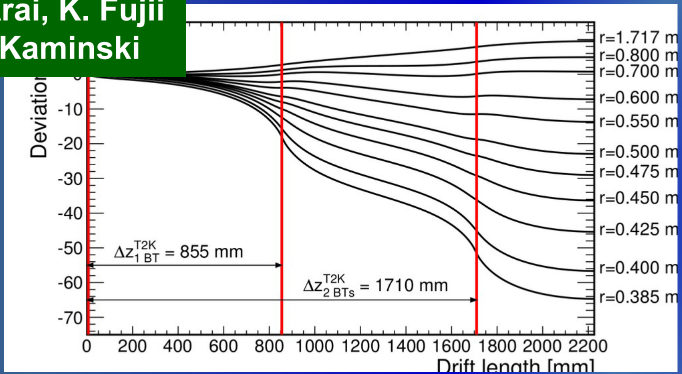
- ✓ ion back flow can be further reduced by applying a double grid.
- ✓ Protection layer resistivity to be reduced
- ✓ New Timepix4 developments

Pixel TPC for Z-Pole Running at CEPC and FCC-ee

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

- At ILC beam-beam effects are dominant: primary ion density 1-5 ions/cm^3 → track distortions < 5 μm
- Gas amplification 10^3 → ILC without gating leads to track distortions of 60 μm → gating device is needed

D. Arai, K. Fujii
J. Kaminski



Track distortions @ CePC / FCC-ee:

✓ HZ-pole running → γγ-background is very small → pad / pixels are OK – ion bkg. comparable to ILC @ 250 GeV

✓ Z-pole running (@10^{36})→ primary ion density 1000 ions/cm^3 → serious tracks distrotions O(mm); space charge effects could be calibrated (e.g. ALICE) ???

✓ Study pixel - TPC to replace pad - TPC for Z-pole running @ CEPC

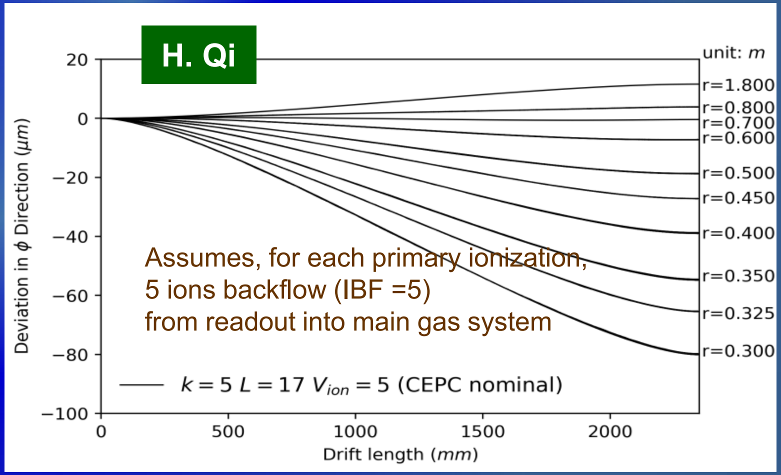
Crucial considerations for FCC-ee / CEPC @ Z pole running:

- primary ionization of the gas;
- ions from the gas amplification stage;
- power consumption (no power pulsing possible;
- operation at 2 T during the Z-peak running;

✓ Ion backflow (IBF) can give a lot of additional charge → so IBF must be controlled (IBF = 5/1.5 → 80 / 14 um)

✓ Measuring IBF for Gridpix is a priority, expected $\mathcal{O}$(1‰)

H. Qi

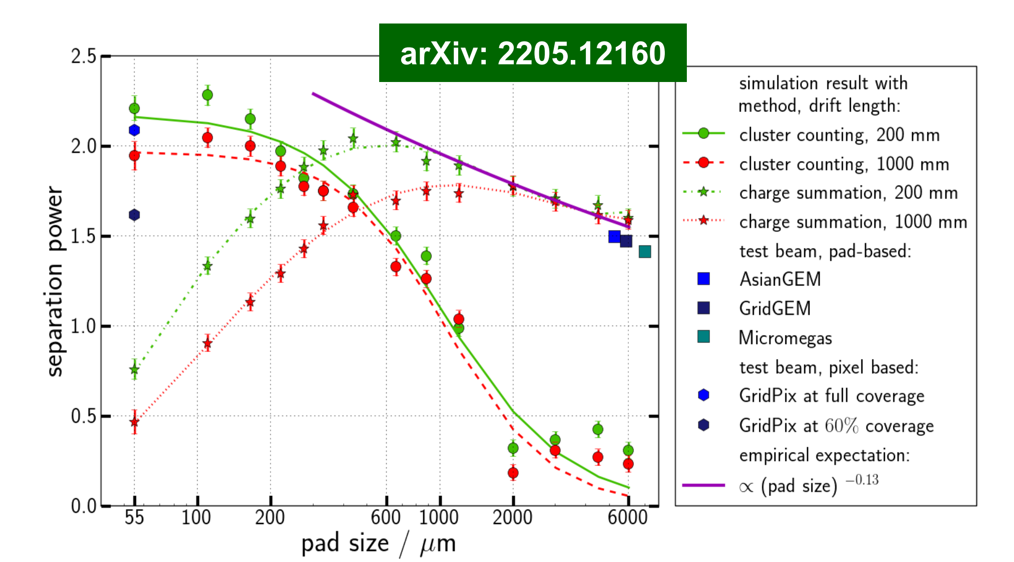


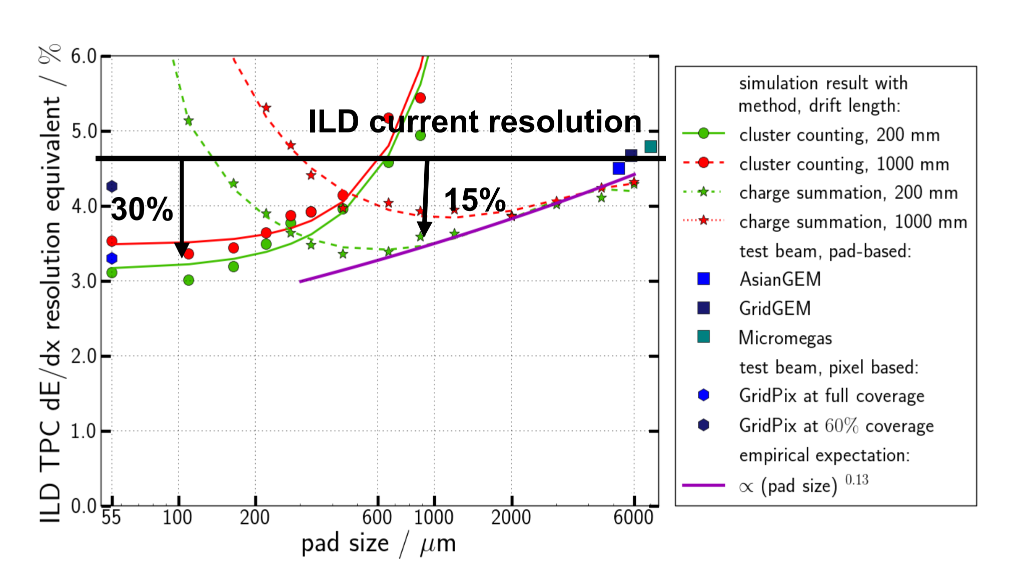
Future R&D needed:

- Optimal pad size to improve track resolution;
- Pixel size > 200 um or large → cost reduction

Cluster Counting / Charge Summation / Granularity

Simulation of PID with gaseous tracking and timing in ILD Prototype





B. Dudar, U. Einhaus

<u>Current full ILD reconstruction:</u>

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

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

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

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

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

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

The Evolution of Drift Chambers at e+e- Colliders

past

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

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

present

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

future

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

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

- closed
- closed
  the tra
- square
- small

... but

- portion
  envelo
- small
  use of
  contrib
- some

Lesson #3 – small cells and He gas

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

... but

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

Lesson #4 – full stereo configuration

- no gap
  electro
- consta
- larger
- maxim
- two st

... but

- open t
  from th
- consta
  z (radi
- consta

Lesson #5 – summary

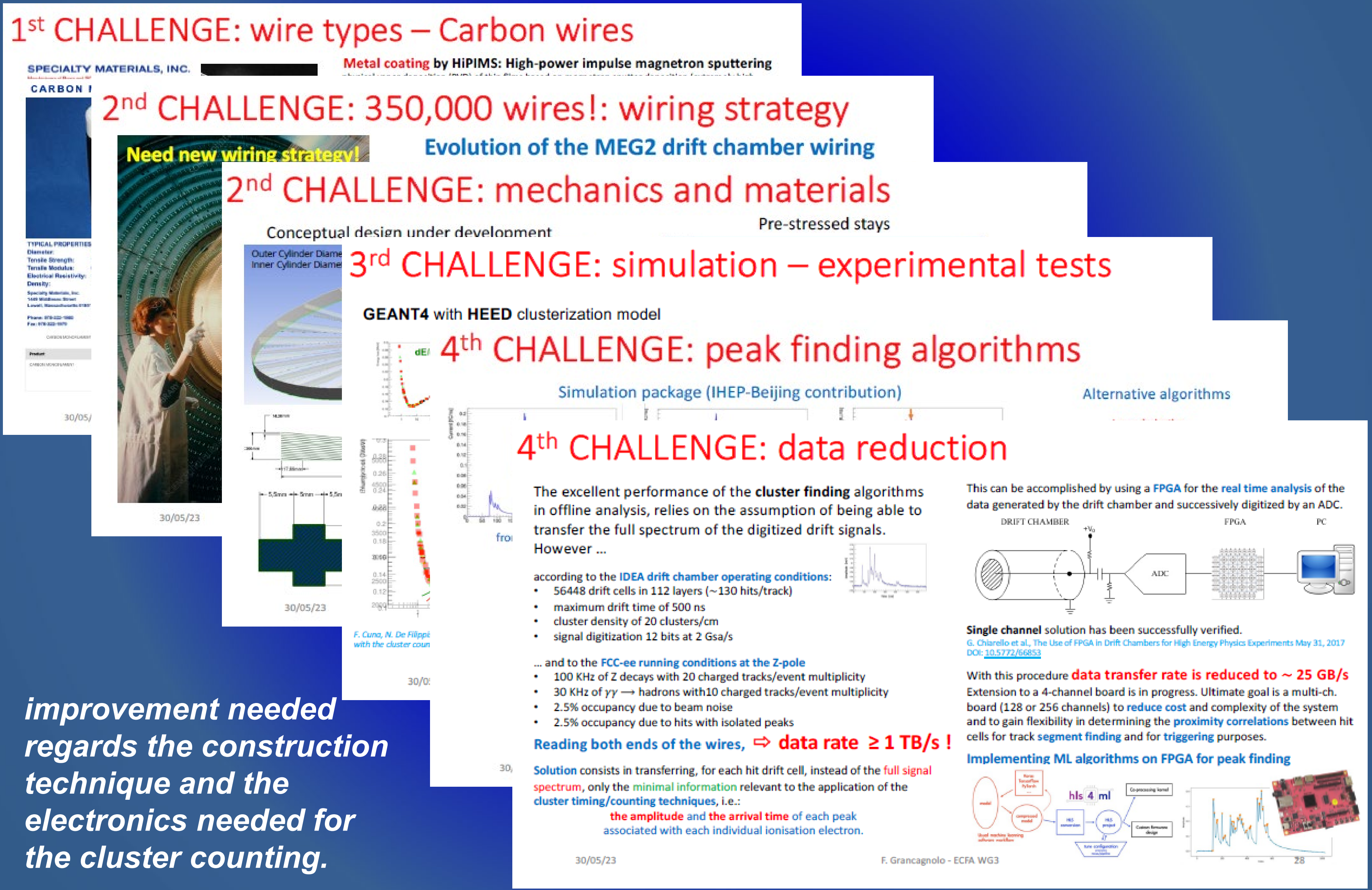
- the configuration offering the best performance in terms of **momentum resolution** is one with small, single sense wire closed cells, arranged in contiguous layers of opposite sign stereo angles, obtained with constant stereo angle transverse projection
- the gas mixture is based on helium with a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

F. Grancagnolo @ INSTR2020

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

IDEA Drift Chamber Concept

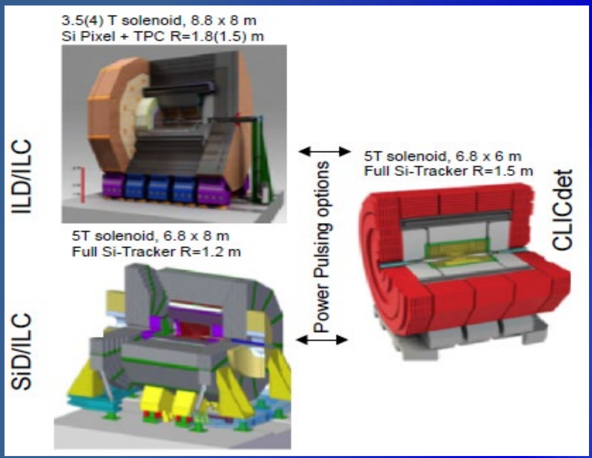
F. Grancagnolo, https://indico.cern.ch/event/1264807/contributions/5344229/attachments/2656054/4599876/Tracking_May23_compressed.pdf

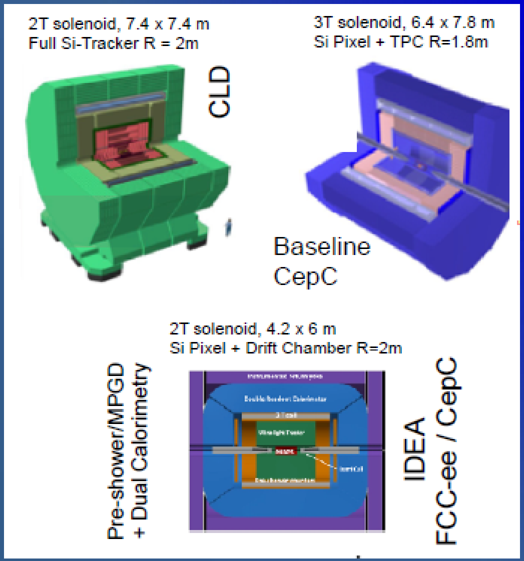


improvement needed regards the construction technique and the electronics needed for the cluster counting.

Vertex & Tracking Challenges @ Future Lepton Colliders

Beam parameters	ILC		CLIC			FCC-ee			CepC	
Energy(TeV)	0.25	0.5	0.38	1.5	3	0.091	0.24	0.36	0.091	0.24
Luminosity (x 10^{34} cm^{-2} s^{-1}) per IP	1.35	1.8	1.5	3.7	5.9	230	8.5	1.7	32	1.5
Bunch train frequency (Hz)	5		50							
Bunch separation (ns)	554		0.5			20	994	3000	25	680
Number of bunches / train - beam	1312		312	312		16640	393	48	12000	242





All-Silicon vs Silicon + Gaseous Tracking:
some open technology questions to be addressed:

All-Silicon tracker (ILC / SiD, CLICdp, FCC / CLD, CEPC / FST concepts)

- ✓ ILC: number of layers; thin detectors, time-stamping capability, minimize material budget (2D/ stitching); power savings / engineering;
- ✓ Circular colliders: continuous operation → power-pulsing is not possible (aim less power consumption & active (increased) cooling) → increased material budget;

Silicon + TPC (ILC /ILD, CEPC baseline concepts)

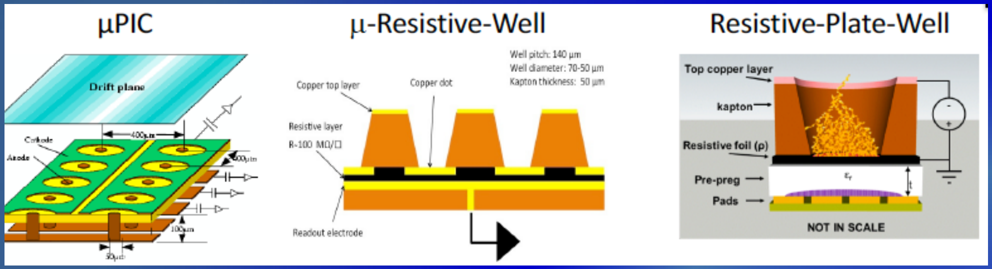
- ✓ ILC: use of GEM-grid gating; dE/dx performance looks OK;
  CC: can TPC stand for (extremely) high readout rate; ion feedback – can it cope @ Z-pole;
- ✓ Calibration and detector alignment;
- ✓ Low power consumption FEE ASIC;
- ✓ Mechanical (field cage rigidity) and distortion (field cage quality, module flatness) challenges;

Silicon + Wire/Drift Chamber (FCC / IDEA, CEPC / IDEA)

- ✓ Can it cope with high rates @ Z-pole;
- ✓ Half as many hits as in TPC → more Si-layers → momentum resolution sufficient ?;
- ✓ Aging effects: hydrocarbon-based mixtures are not trustable for long-term operation in DC → search for different gas mixtures;
- ✓ Very long wires (~4m), study/optimize wires material;
- ✓ dE/dx by cluster counting (depends on N_{hits} in DC);

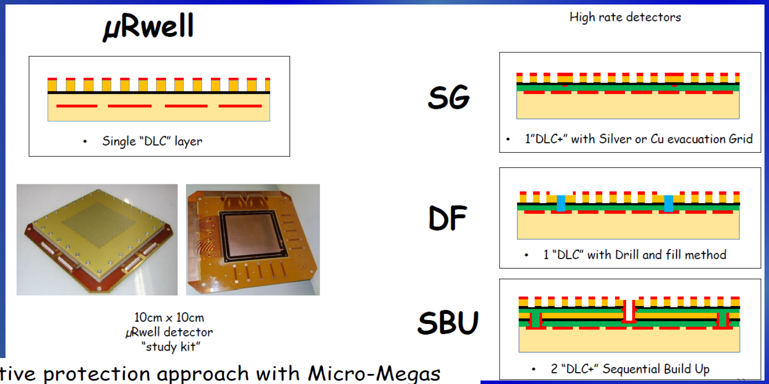
MPGD Technologies @ Future R&D Trends

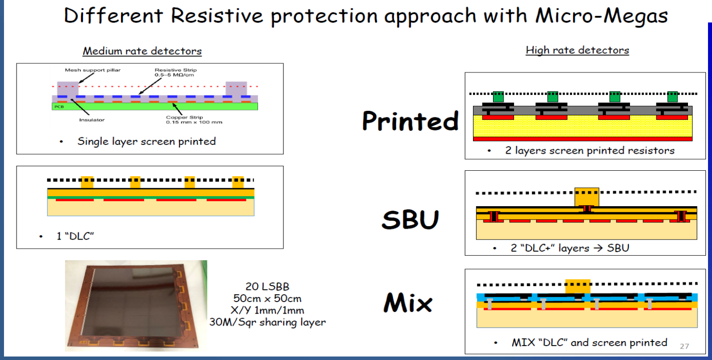
✓ ***RESISTIVE MATERIALS*** **and related detector architectures for single-stage designs (µPIC, µ-RWELL, RPWELL, resistive MM)**
→ improves detector stability; single-stage is advantage for assembly, mass production & cost.



➢ ***Diamond-like carbon (DLC) resistive layers***
→ Solutions to improve high-rate capability (≥ MHz)

Resistive DLC Collaboration





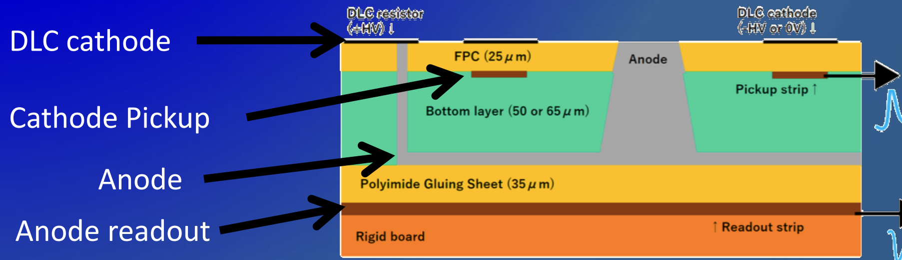
➢ **New manufacturing techniques & structures:**

- Solid-state photon and neutron converters, ***INNOVATIVE NANOTECHNOLOGY COMPONENTS (graphene layers);***

- Material studies (low out-gassing, radiation hardness, radio-purity, converter robustness and eco-friendly gases.

- Emerging technologies related to novel PCs, MicroElectroMechanical Systems (MEMS), sputtering, 3-D printing of amplifying structures and cooling circuits

Diamond-like carbon (DLC) resistive layers
→ Solutions to improve high-rate capability (≥ MHz)



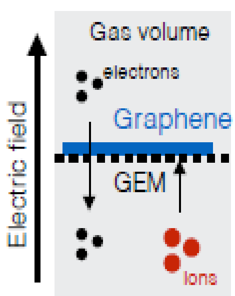
Graphene-based Functional Structures and Nanostructures for novel MPGD Concepts

Graphene layers for: ion-backflow suppression, protection of photocathodes, solid conversion layers

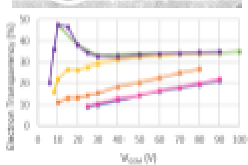
PhD project of Giorgio Orlandini (FAU Erlangen-Nürnberg) in EP-DT-DD Gaseous Detector Development lab

The unique properties of two-dimensional materials such as graphene as well as carbon-based nanostructures offer new perspectives for novel gaseous radiation detectors. This may include performance improvements for detectors for HEP experiments as well as new application fields combining wideband sensitivity of advanced materials with high gain factors and granularity offered by Micro Pattern Gaseous Detectors.

Application 1:
Suspended graphene for ion back-flow suppression and gas separation



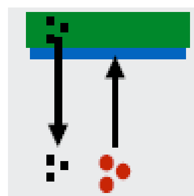
Previous work

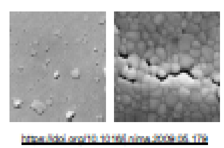


https://doi.org/10.1016/j.nima.2015.11.077

Suppressing ion back flow can significantly **improve high-rate capabilities** and **reduced electric field distortions** in Time Projection Chambers.

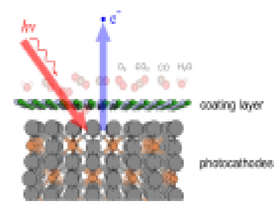
Application 2:
Protection of photocathodes with graphene layers





Damage of CsI

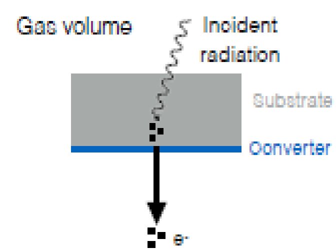
Protection and decrease of work function by coating layer



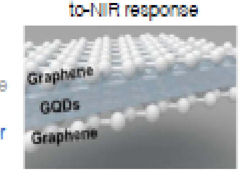
https://www.nature.com/articles/s41699-018-0062-6

Atomically thin coating layers could **protect sensitive photocathodes** such as CsI against environmental factors and ion bombardment, which is important for preserving specifications of precise timing detector in harsh ion-back flow conditions. Additionally, **modifications of the work functions**of converter layers can be used to increase QE.

Application 3:
Graphene and nanostructures for photoconversion and as solid converters



Possible system with UV-to-NIR response



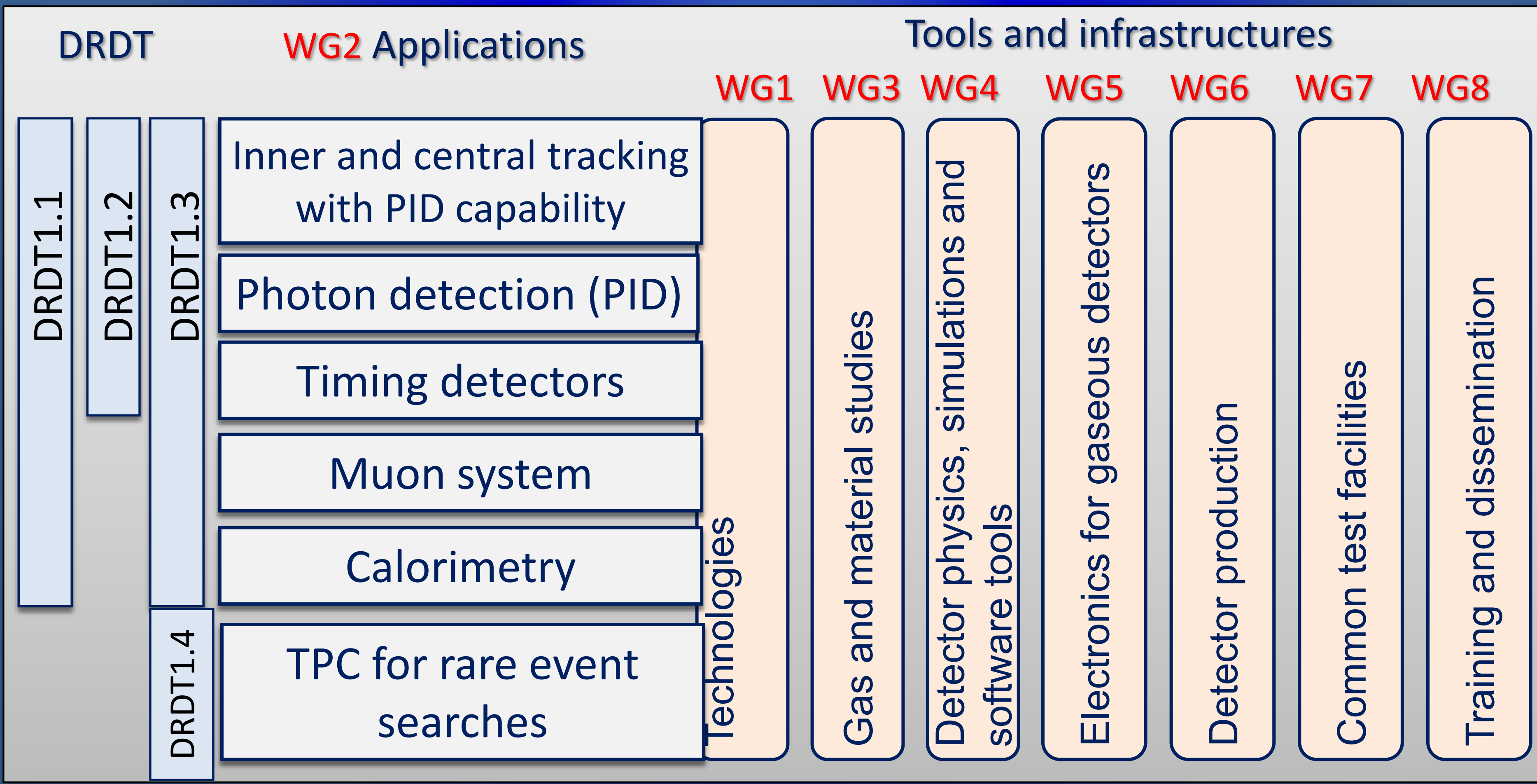
https://www.nature.com/articles/srep05603.pdf

Graphene quantum dots (GQD), carbon nanotubes and graphene have been shown to exhibit **broadband sensitivity** and could be used as versatile **conversion layers**. Utilising solid conversion layers enables high **detection efficiencies** and can be used for **precise timing** with gaseous radiation detectors.

First work on GEM & graphene layers: NIMA824 (2016) 571

DRD1 Scientific Organization: Working Groups

Structure in **WGs**, **a**lignment with the scientific program of the ECFA roadmap through the applications, related to future facilities challenges outlined by R&D Themes (DRDT), but also to the GSRs



DRD1 Scientific Proposal: Advanced Stage

Structure of the DRD1 document:

- **Executive summary**
- **Research topics and Work plan**
  - 8 sections: one per Working Group
  - <u>WorkPackages (strategic R&D in ECFA Roadmap described in 3.2</u>
- **Scientific organization**
- **Resource and infrastructures**

CERN

DRD1

DRD1 R&D PROPOSAL

DRAFT

Abstract

The proposal document provides a comprehensive overview of the state of the art and challenges for various gaseous detector technologies, as well as a detailed list of R&D tasks grouped into Work Packages (WPs). The latter are 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 collaboration research program for the next 3 years.

Please, pay particular attention to your institute's research interests in chapter 3.2 devoted to applications, which is fully aligned with the ECFA Detector R&D roadmap themes and serves as the basis of the Work Packages.

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Contents

The draft document already sent to the contact persons

DRD1 Community proposal discussion (Jun. 22-23): https://indico.cern.ch/event/1273991/

Example of DRD1 Work Package: Muon Systems

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3 y	Interested Institutes
T1	New resistive materials (RPC) and production techniques for resistive layers	- Develop low-cost resistive layers (technology dependent) - increase rate capability	WG3 (3.1C, 3.2D), WG7 (7.1-5)	1.1, 1.2	- HPL, low resistivity glass - Semiconductors - Printed resistive patterns	- Design, construction and test of prototypes with new production techniques	INFN-RM2, INFN-PD, KOBE, Pavia
T2	New resistive materials (MPGD)	- Stable up to gains of $\mathcal{O}(10^6)$ - High gain in a single multiplication stage	WG3 (3.1C, 3.2D), WG4, WG7 (7.1-5)	1.2		- Design, construction and test of prototypes with new resistive materials	USTC, INFN-PD, INFN-RM3, INFN-LNF, INFN-FE
T3	New front-end electronics	- 1 fC threshold - High-sensitivity electronics (together with new detector structures) to achieve stable and efficient operation up to $\mathcal{O}$(MHz/cm^2)	WG5, WG7 (7.1,2)	1.1	- Integration of the FEE in the detector Faraday cage - Integration of electronics and readout PCB	- Conceptual electronics design based on gas detector simulation and experimental measurements - Development and test of a front-end prototype	Oviedo, IFIN-HH, INFN-FE
T4	Scalable multichannel readout system	- Front-end link concentrator to a powerful FPGA with possibilities of triggering and $\mathcal{O}$(20 GBit/s) to DAQ	WG5	1.1, 1.2	- FPGA-based architecture - FPGA with embedded processing for triggering and ML - Basic firmware and software can be bootstrapped from existing readout system	- First prototype by end of 2024 for commissioning at test beam	IFIN-HH
T5	Eco-friendly gases	- Guarantee long-term operation - Explore compatibility and optimized operation with high-GWP gases	WG3 (3.1A, 3.1B, 3.2C), WG4, WG7 (7.1-4)	1.1	- Ageing studies - Leak mitigation and maintenance of existing systems	- Test and characterization of gaseous-detection technologies with high-GWP gases (broadly)	CERN, Wurzburg, INFN-BA, INFN-LNF, Pavia
T6	Manufacturing	- Construction of large-area detectors at low cost - Modular design - Technology transfer scheme and training center for production	WG3 (3.2E), WG6, WG8	1.3	- Optimization of the manufacturing procedure to minimize time-consuming or costly steps	- Design and manufacturing of large area detector - Large area DLC production	Heidelberg, USTC, Weizmann, GSI, INFN-LNF
T7	Thinner layers and increased mechanical precision over large areas	- Test to experience the ultimate limits to thinning down the detector	WG3 (3.2E), WG5, WG7 (7.1,2)	1.3			
T8	Longevity on large detector areas	- Study discharge rate and the impact of irradiation and transported charge (C/cm^2)	WG1, WG3 (3.1B, 3.1D, 3.2B), WG4, WG7 (7.1,3)	1.1	- Discharge probability - Ageing		

Challenges for the future muon systems

- Extend state-of-the-art rate capability and longevity by minimum one order of magnitude or more in the highest eta region (up to an order of MHz/cm^2)
- Enable detectors efficiently working with suitable low GWP mixtures
- Two objectives above can be favored in 3 ways:
  - low noise electronics integrated in a highly stable and noise immune Faraday cage
  - detector geometries increasing the signal collection
  - use of innovative resistive material for suppressing discharges on the electrodes.
- Time resolution O(10-100ps) for timing applications in a very high rate collider, (e.g., for identifying bunch-crossing, pile-up mitigation, and improved determination of the particle velocity)
- Large-scale serial production.
- Large series industrializes production

Applications: future electron colliders (ILC, FCC-ee, CepC), Muon collider, Hadron Physics, FCC-hh). Technologies: RPC, Micromegas and GEM, mRWELL, gridsPix, m-PIC, FTM…

Example of DRD1 Work Package: Inner/Central Tracking

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	IBF reduction	- Gain×IBF ≈ 1-2 - IBF optimization together with energy resolution and discharge stability	WG4, WG7 (7.1-2,5)	1.2	- Hybrid stacks - Gating GEM - Distortion corrections - Space-charge monitoring - Development of simulation tools - Operation in magnetic fields	- Provide a large-area prototype with a uniform IBF distribution of G*IBF=5 keeping the energy resolution at a tolerable level - Present a structure with stable settings for G×IBF of 1-2 - Determine the ion blocking power of a GEM-based gate - Provide systematic studies and simulations of IBF performance for the most common structures in (high) magnetic fields - Introduce an IBF calculator (Garfield-based) for optimization of the HV parameters	IFUSP Sao P., GSI, Uni Bonn, IRFU/CEA, USTC, Uni Tsinghua, KEK, DESY, NIKHEF, GANIL, RWTH Aachen, INFN Padova, IP-PLM Poland, CERN, PSI, Bursa, Stony Brook
T2	Pixel TPC development	- Produce 50000-60000 GridPixes to read out a full TPC - Achieve dN/dx counting-resolution < 4%	WG5, WG7 (7.1-2,5)	1.1	- InGrids (grouping of channels) - Low-power FEE - Optimization of pixel size (>200 µm) or cost reduction	- Provide a large-area pixel-based (InGrid) readout module - Measuring IBF for Gridpix. Reduction with double-mesh - Present dN/dx measurements in beam	Uni Bonn, NIKHEF
T3	Optimization of the amplification stage and its mechanical structure, and development of low X/X_0 field cages (FC)	- Uniform response across the a readout unit area. - Keep $\sigma_{dE/dx} \approx 4\%$ - Point resolution of < 100 µm - Minimize static distortions by reducing insensitive areas - Minimize E×B - Achieve E-field homogeneity at $\sim 10^{-4}$ level	WG1, WG4, WG6, WG7 (7.1-2,5)	1.1 1.[illegible]	**Minimization of static distortions:** - Algorithms for distortion corrections - Field shaping wires - Minimize GEM frame area (use thicker GEMs) - Laser systems **Main ampl. stages:** - Encapsulated resistive-anode MMG - Multiple GEM - GridPix - Hybrids **FC:** - high-quality strips, suspended strips - module flatness	- Provide a solution for a large-volume TPC with $\mathcal{O}(10^6)$ pad-readout by means of pre-production of several readout modules of comparable quality	IRFU/CEA, Uni Bonn, IHEP CAS, USTC, GANIL, IN2P3, CNRS, GSI, RWTH Aachen, INFN Roma, INFN Padova INFN Bar, IPPLM Poland, PSI, Bursa, Stony Brook
T4	Low-power FEE	- <5 mW/ch for >10^6 pad TPC - ASIC development in 65 nm CMOS	WG5	1.3	- Continuous vs. pulsed	- Present stable operation of a multi-channel TPC prototype with a low-power ASIC	IHEP CAS
T5	FEE cooling	- Operate 10^6 channels per end-plate	WG5	1.2	- Two-phase CO_2 cooling - Micro-channel cooling with 300 µm pipes in carbon fiber tubes - 3D printing: complex structures, performance optimization, material selection	- Present a prototype of a cooling system for the 10^6 pad TPC option	IRFU/CEA, Lund Univ, INFN Pisa, INFN Lecce, INFN Padova
T6	Gas mixture	Optimize: - Longevity - Ageing - Discharge probability - Drift velocity - Ion mobility	WG1, WG3 (3.1D, 3.2A, 3.2B), WG4, WG7 (7.1-3,5)	1.1	- Discharge probability, ageing, gas properties - Optimization of the HV working point - Optimization wrt. the expected resolution (aim for <100 µm)	- Lower the discharge probability of readout units by 1-2 orders of magnitude down to $\sim 10^{-14}$ per hadron - Avoid secondary discharges in MPGD stacks	CERN, IFUSP Sao P., GSI, TUM, IHEP, GANIL, USTC, IN2P3, IRFU/CEA, CNRS, RWTH Aachen, Uni Bonn, Bose, INFN Roma, INFN Lecce, INFN Padova, INFN Bari, IP-PLM Poland, USC/IGFAE, Bursa, Stony Brook

Challenges for the TPC

- *Good dE/dx resolution, partly driven by a good gain uniformity;*
- *very low (gain x Ion Back Flow) to drastically reduce space charge distortions;*
- *high readout granularity to cope with the particle multiplicity;*
- *electronics with low power dissipation to meet the increased density of readout channels.*
- *large area coverage at reduced low cost, relying on lightweight mechanical structures based on composite materials.7*

Area of application: future electron colliders (ILC, FCC-ee, CEPC). Timeline: 2035-2040, most of the R&D goals should be reached by 2030 to allow for timely construction.