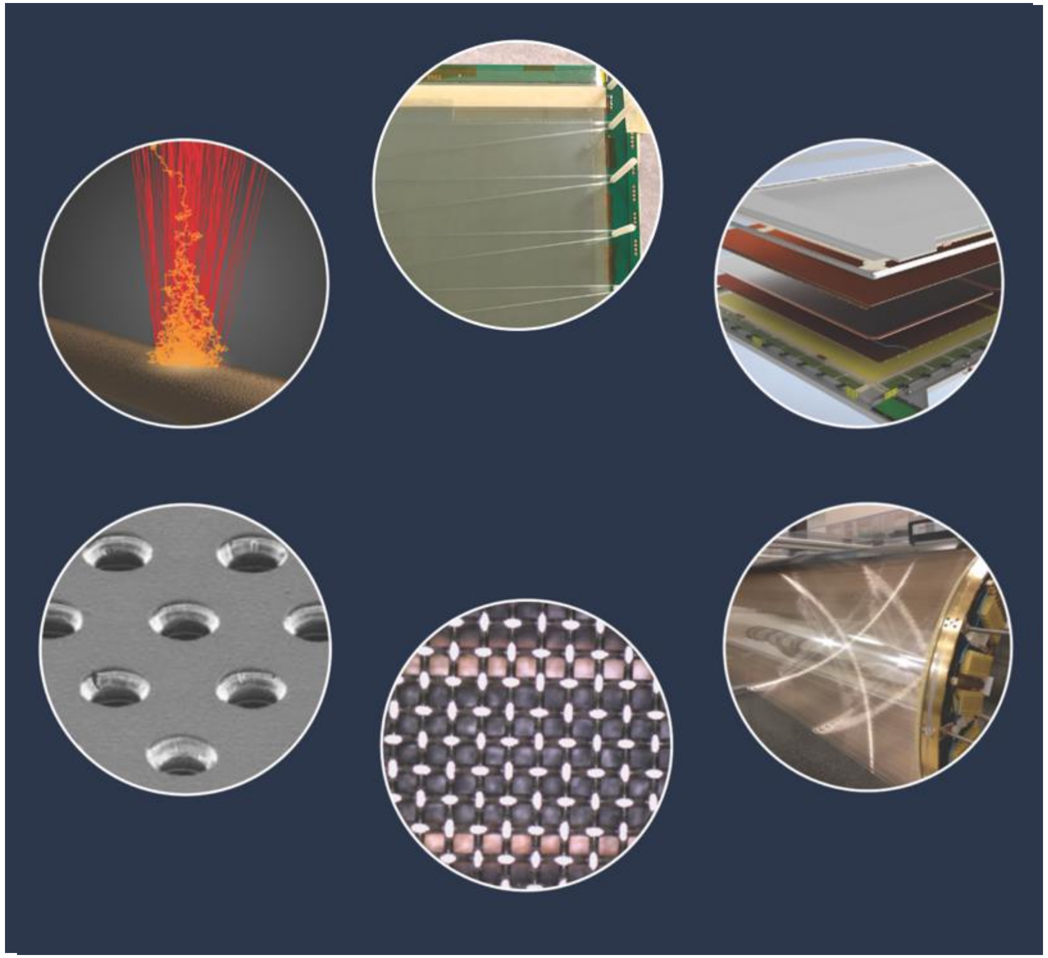
IFD 2025 – INFN Workshop for Future Detectors

Gaseous Detectors

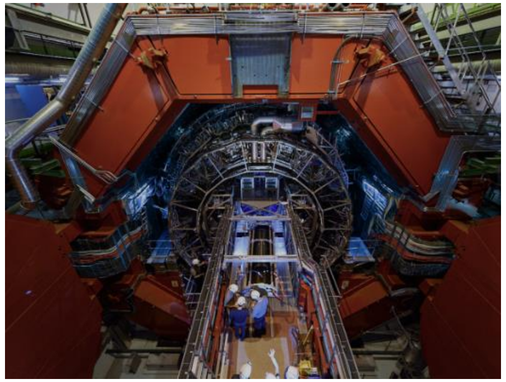
E. Baracchini, M. Iodice, B. Liberti, E. Radicioni

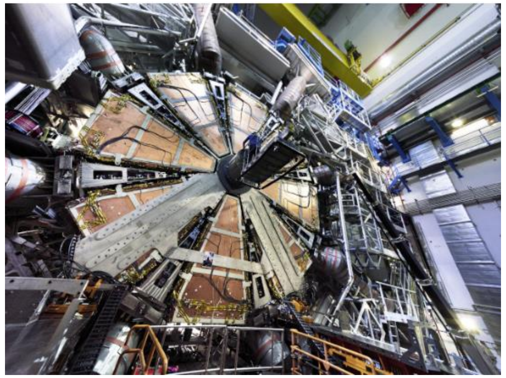


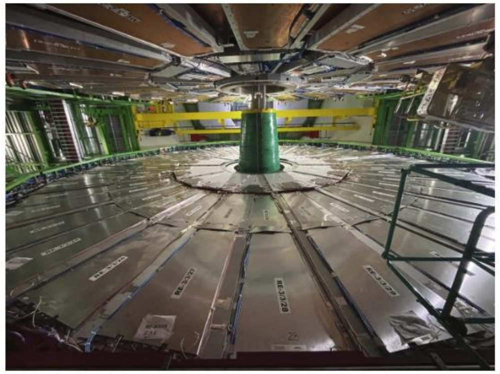
- LARGE AREA MUON SYSTEMS
  - MPGD
  - RPC
  - Wire based detectors (MWPC, Straws, (s)TGC, …)
- INNER AND CENTRAL TRACKING (WITH PID CAPABILITY)
  - MPGD (cylindrical)
  - DRIFT CHAMBERS,
  - STRAW AND DRIFT TUBE CHAMBERS
  - TPC
- TPC: Trackers, Decay chambers, Beyond HEP

Gaseous Detectors at LHC

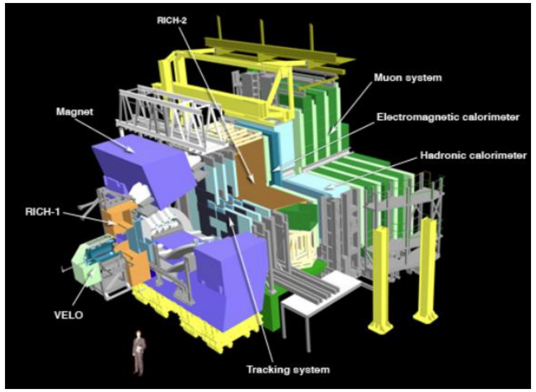
- Gaseous detectors are key devices in current forefront experiments, e.g. at LHC
- Mostly central trackers (TPC) and Muon systems (MS)







CMS iRPC RE-3/1 installation - YETS 2025



ALICE

- CSC (Muon Spectrometer)
- MWPC (RICH HMPID)
- MWPC (veto in Photon Spectrometer
- Drift Chamber (in the TRD for Tracking)
- Timing MRPC (TOF)
- GEM (TPC)

ATLAS

- MDT (Muon Spectrometer)
- CSC (MS – removed after Run2)
- TGC, sTGC (MS)
- RPC (MS)
- TRD straws (TRT - Inner Tracker)
- Micromegas (MS Run3 and beyond)

CMS

- Drift Tubes (Muon Spectrometer)
- CSC (MS)
- RPC, iRPC (MS)
- GEM (MS Run3 and beyond)

LHCb

- MWPC (Muon System)
- GEM (MS - removed after Run2)
- uRWELL (MS - proposed for Run5)

MUON SYSTEMS – MPGD - Current State and Application

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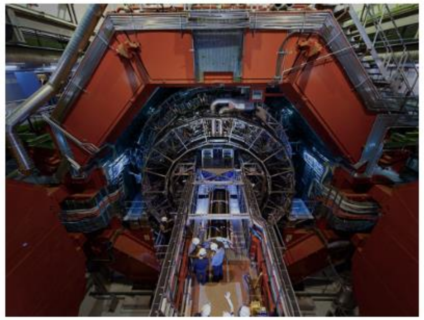

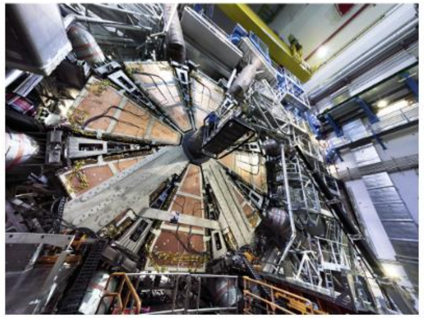

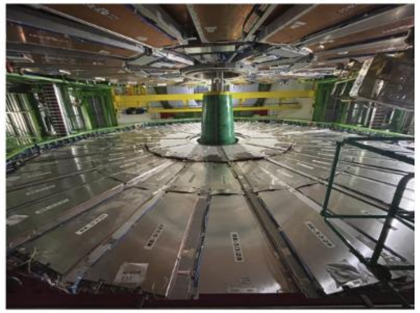

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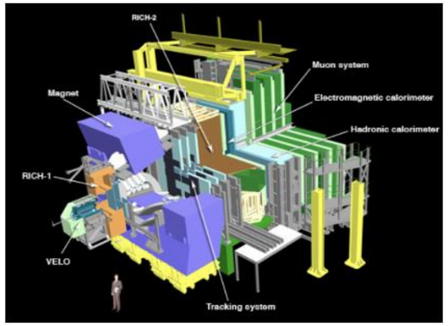

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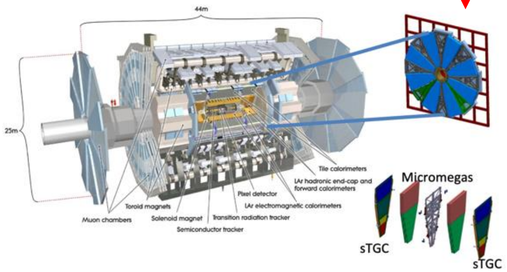
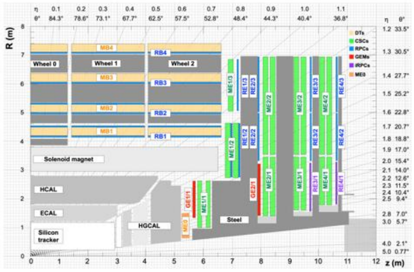
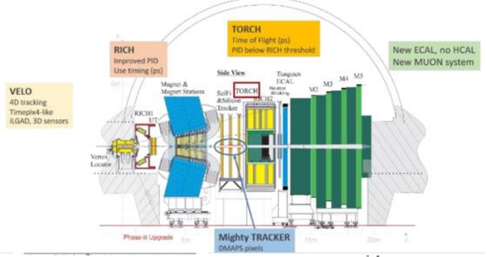


Micromegas in the New Small Wheel (the main ATLAS Phase-1 upgrade)



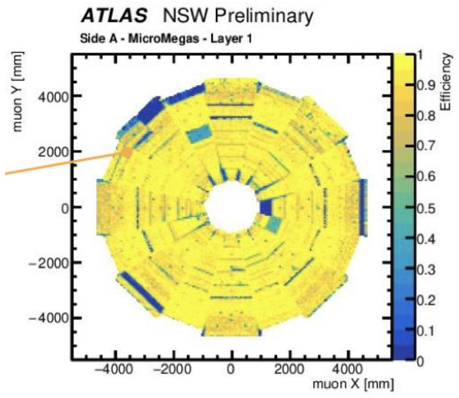
Phase-1: GE1/1 recording LHC Run-3 data since 2022
Phase-2: GE2/1 and M0

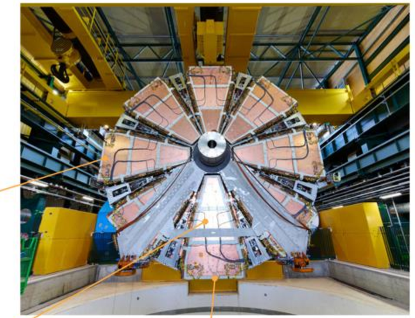
Proposed for the LHCb upgrade for Run5

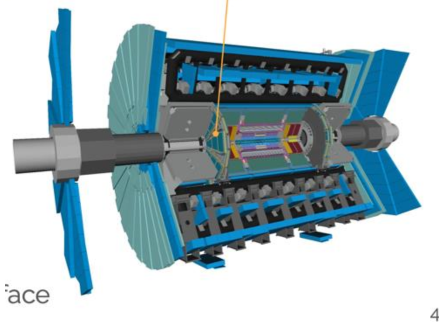


MUON SYSTEMS – MPGD - Current State and Application

Micromegas in ATLAS

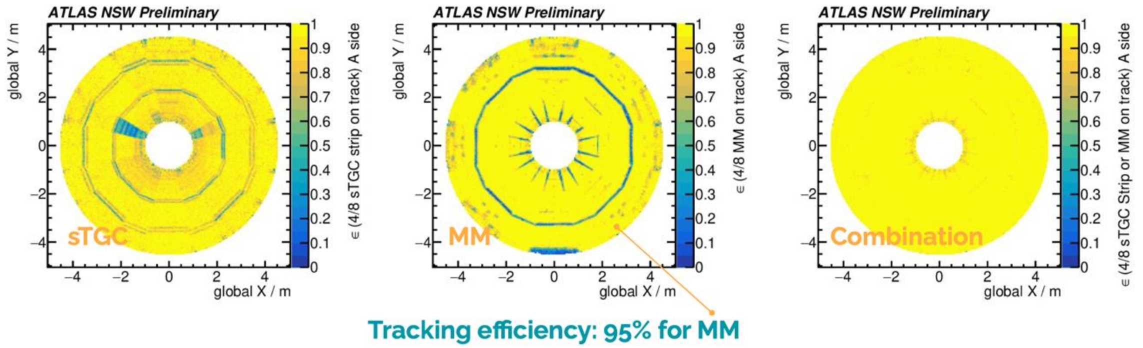




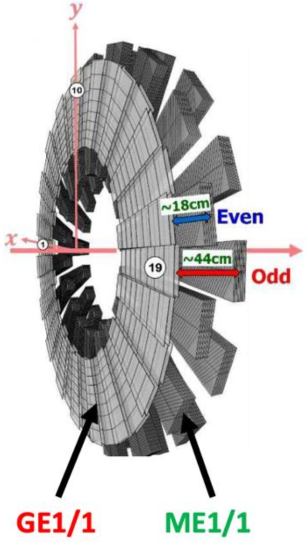


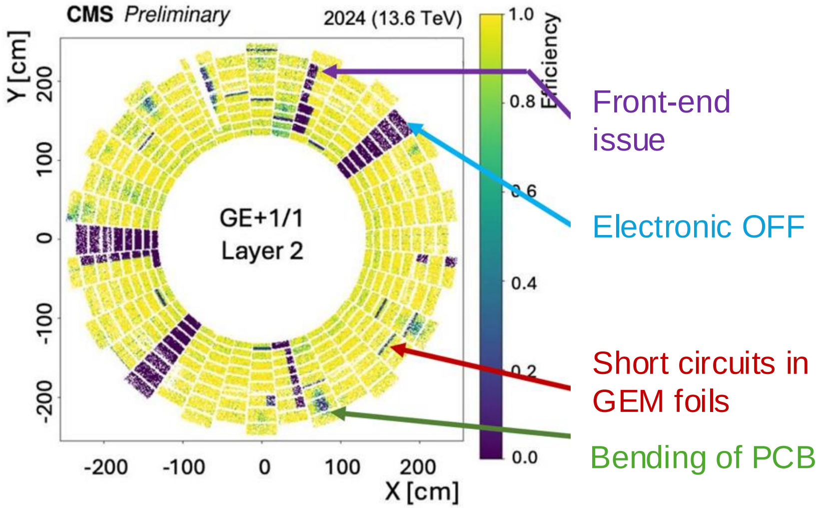
Single layer efficiency

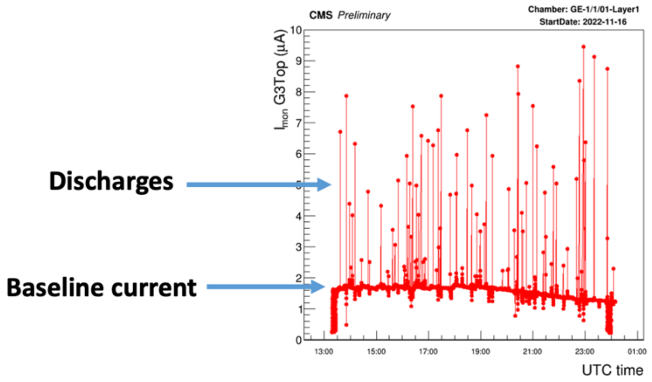
Tracking efficiency



Triple GEM in CMS







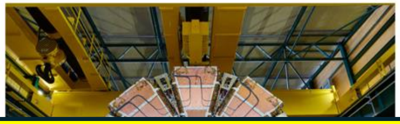
2024 p-p collisions

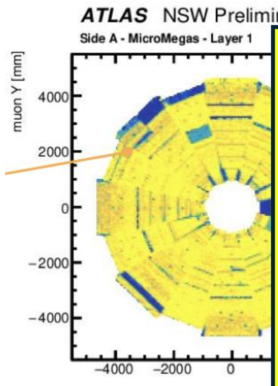
- Instantaneous Luminosity: O(10^{34}) cm-2s-1
- Average rate of discharges: < 3 discharge per hour

Not PERFECT detectors yet. Ongoing R&D for future detectors must focus on improving the technology, enhancing robustness, and achieving better performance for more reliable systems

MUON SYSTEMS – MPGD - Current State and Application

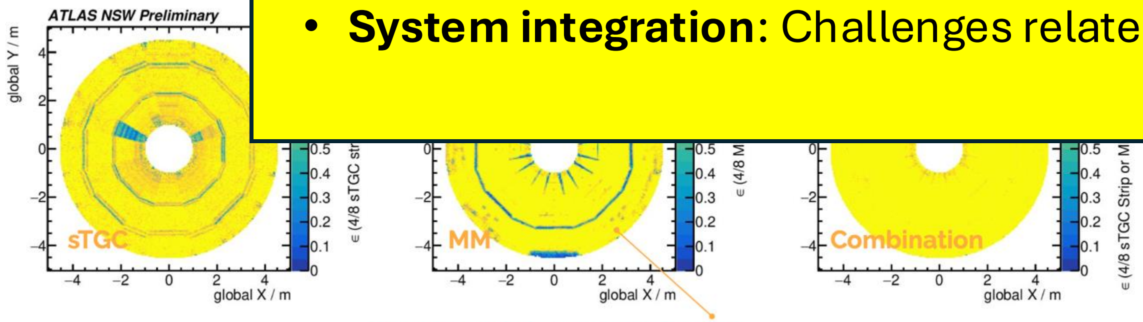
Micromegas in ATLAS





Single layer e

Tracking effi



Tracking efficiency: 95% for MM

Triple GEM in CMS

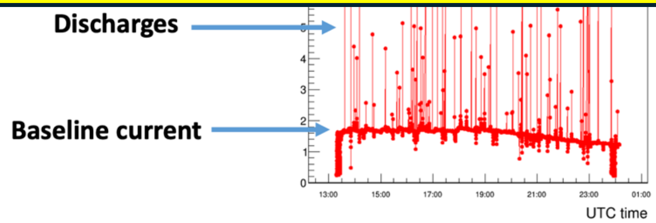
end

onic OFF

circuits in
oils

ng of PCB

(10^{34})
cm-2s-1



- Average rate of discharges: < 3 discharge per hour

Challenges and Potential Issues in Large MPGD Systems:

- **Scaling up**: Transition from small-size prototypes to large-area detectors.
- **Mechanical precision**: Ensuring structural integrity and alignment.
- **Discharges & stability**: Managing high gain while maintaining a wide operational margin.
- **Resistive scheme:** Optimization (in-depth, rigorous and detailed tests) and implementation.
- **Production process**: Quality control and assessment at each phase.
- **High-voltage power scheme**: Design and reliability considerations.
- **System integration**: Challenges related to front-end electronics, connections, and DAQ…

Not PERFECT detectors yet. Ongoing R&D for future detectors must focus on improving the technology, enhancing robustness, and achieving better performance for more reliable systems

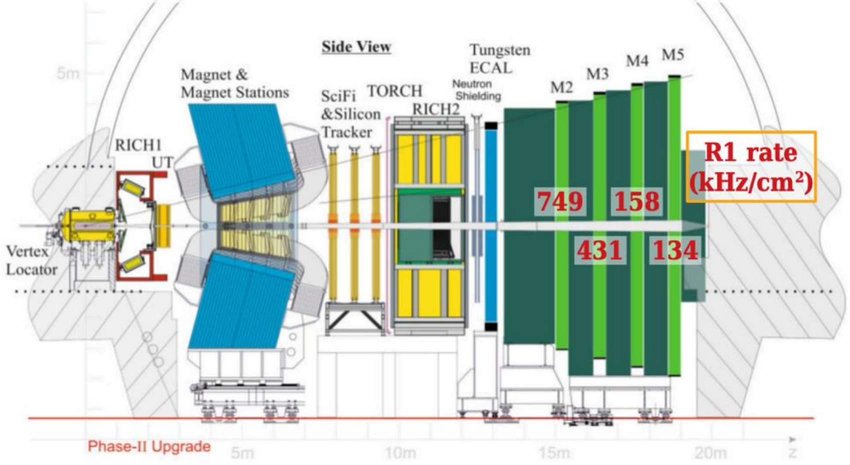
MUON SYSTEMS – MPGD – a proposal for LHCb

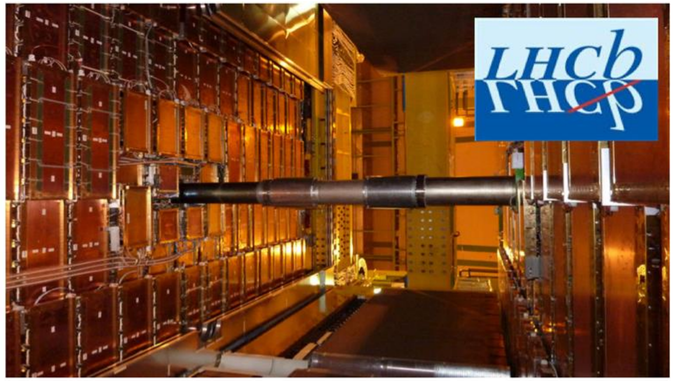
The u-RWELL technology, in its hybrid structure with a GEM preamplification stage, will make its first appearance in HEP experiments

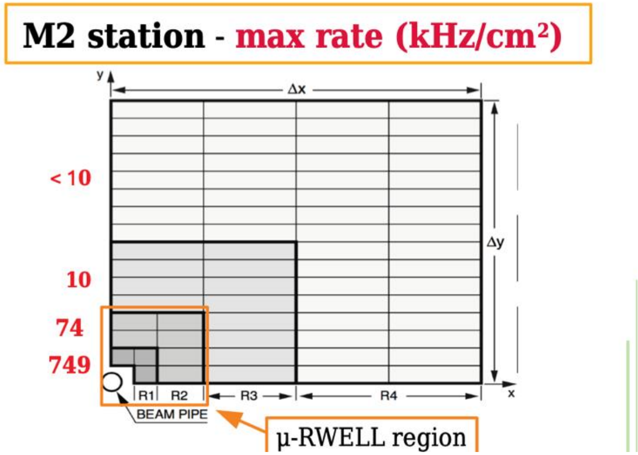
LHCb upgrade II (Run5-6)

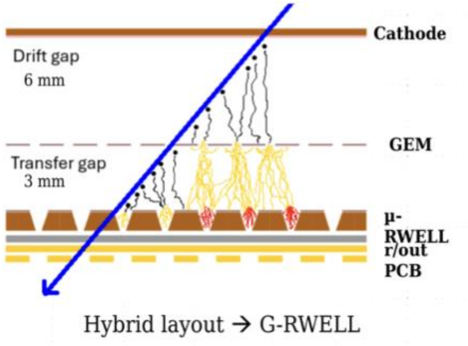
LHCb muon RUN 5-6 option: μ-RWELL → Detector requirements:
- Rate up to **1 MHz/cm²** on detector single gap
- Rate up to **700kHz** for FEE channel
- Efficiency (4 gaps) > **99% within BX** (25 ns)
- Stability up to 1 C/cm² accumulated charge in 10y of operation

Detector size & quantity (4 gaps/chamber)
- R1 + R2 of M2-M5: **576 det.**, size 30x25 to 74x31 cm², **90 m² det**









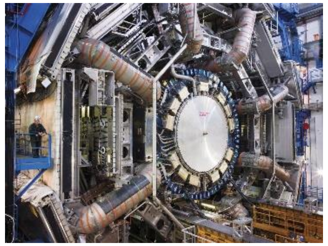
The G-RWELL structure

The **Upgrade 2 project** includes:
- **Recovery of existing detectors (MWPC) where possible.**
- **In the inner regions,** rate capability and deadtime constraints require new detectors.
- **Technology for the two innermost regions:** G-RWELL (a hybrid detector: μ-RWELL with an additional GEM pre-amplification stage).
- **240 new chambers** out of a total of **1,100**, covering approximately **60 m²** out of the total **400 m²**.

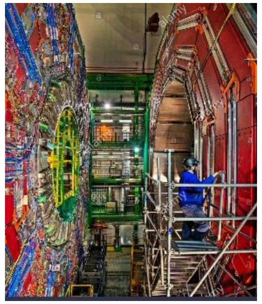
From M. Giovannetti
MPGD2024, Hefei 14-18 October 2024

MUON SYSTEMS – RPC – Current State and Application

- Present and recent past Application at colliders

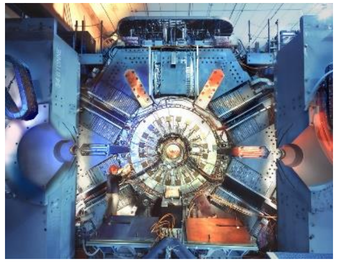


ATLAS
LHC 7000 m^2
HL-LHC1400 m^2
Tracking trigger



CMS
LHC 4000 m^2
HL-LHC1000 m^2
Tracking trigger

ALICE
LHC 144 m^2
HL-LHC new RPCs
Tracking trigger



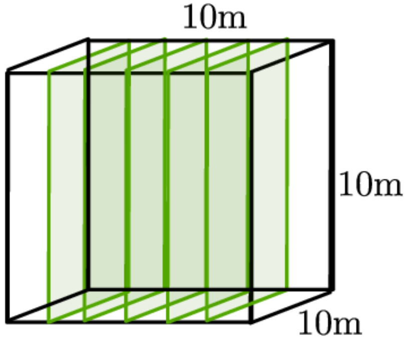
BaBar
SLAC 2000 m^2
Instrum. iron
μ identifier

- PRESENT AND RECENT PAST COSMIC RAYS AND UNDERGROUND

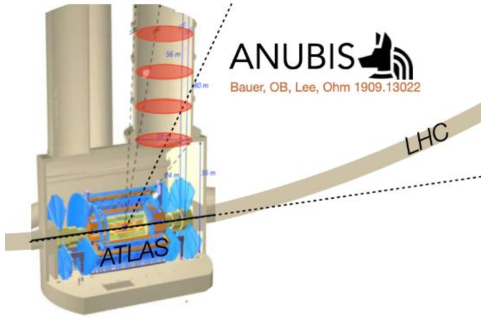
OPERA
CERN ν beam
Instrum. iron
μ spectrometer

ARGO Ybj
CR exp. 7000 m^2
4600 m altitude
3D reconstruct.

- ACTIVE PROPOSALS FOR FUTURE EXPERIMENTS USING PRESENT TECHNOLOGY



CODEX-B
HL-LHC. 3000 m^2
Search for DM
Sealed tracking volume



ANUBIS
HL-LHC. 5500 m^2
Search for DM
Sealed tracking volume

Mostly used as extensive (up to ~ 7000 m^2)
Trigger systems with time resolution up to 500 ps

MUON SYSTEMS – Multi-gap RPC / TOF – Current State and Application

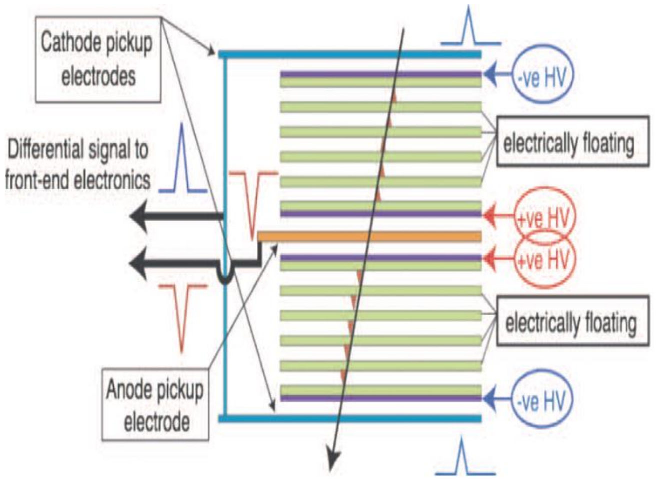
MRPC Several thin gas gaps. Thin plates in glass (Williams et al) in 1996.

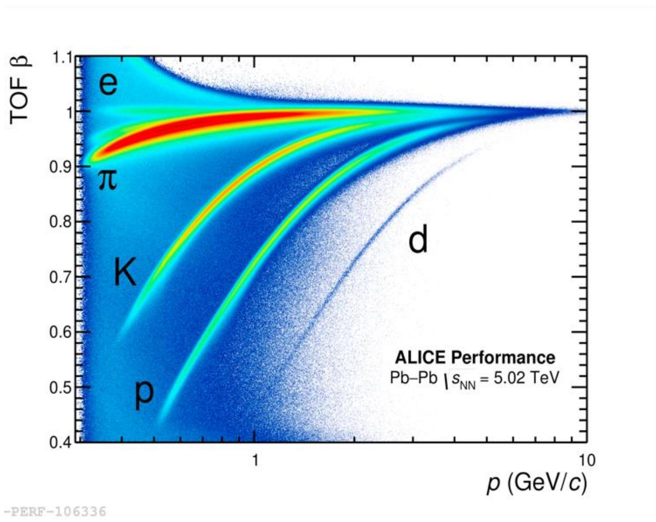
- Time resolution down to tens of ps for MRPC.

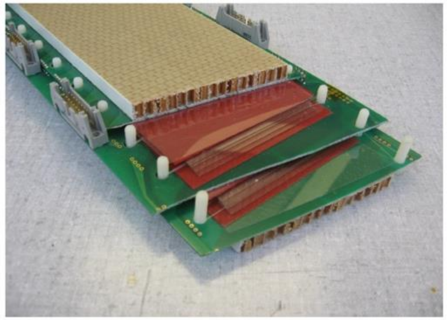
Here only a couple of examples

ALICE MRPC: 2x5-gap (250 μm each)

- Time resolution: 50 – 80 ps





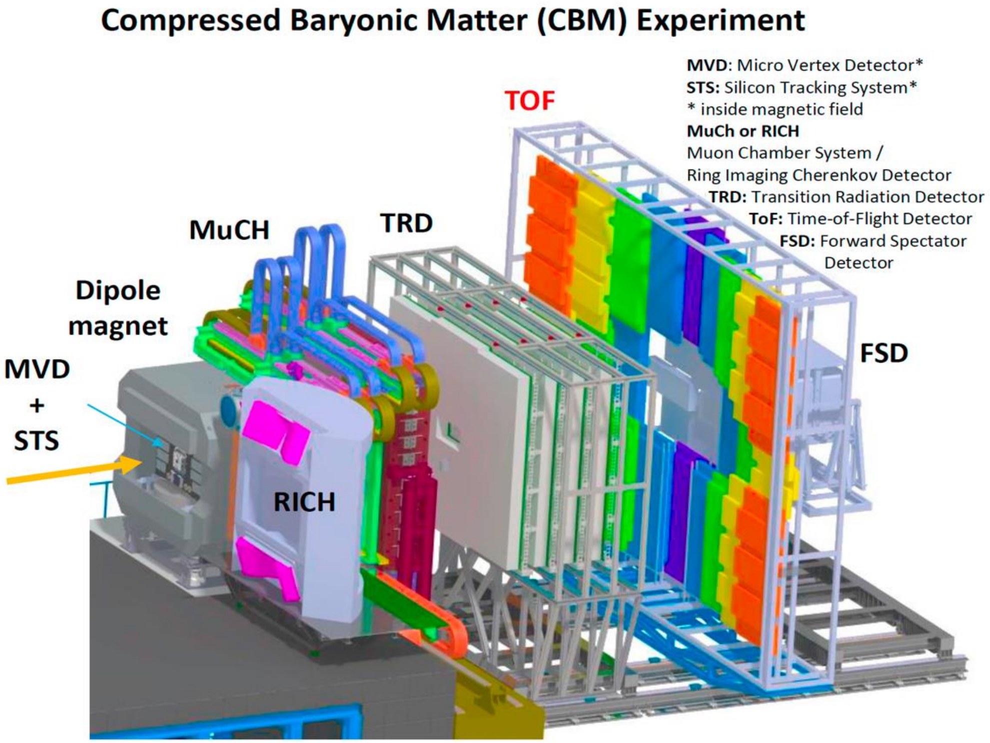


ALICE@CERN

10.1016/S0168-9002(01)01753-3

TOF for CBM experiment at FAIR (GSI)

- Time resolution: 50 – 80 ps



MUON SYSTEMS – RPC and Multi-gap RPC – Current State and Application

Key features

- 50 ps time resolution (500 ps for single gap)
- Single Gap RPC Efficiency > 98%
- 2D tracking, resolution up to 0.1 mm
- Proportional response to high track density
- Large size robust and Low cost
- Thin and light

Present Limits

- Rate capability: Electrode resistivity responsible for the proverbial stability of RPCs also limits its rate capability
- Longevity: RPC materials are insensitive to radiation, but radicals produced in the discharge affect the electrode quality increasing noise, while the amount of conduced charge can deplete the carriers affecting resistivity

Challenges and Potential Issues in Large RPC and M-RPC Systems:

- Production process: Quality control and assessment at each phase.
- High-voltage power scheme: Design and reliability considerations.
- System integration: Challenges related to FE electronics and DAQ

- RPCs (all versions) are a strong candidate technology for FFC and MuColl experiments
- **R&D is needed MATERIALS, FE ELECTRONICS, NEW STRUCTURE, NEW GAS MIXTURES**

MUON SYSTEMS – RPC and Multi-gap RPC – a paradigm for Greenhouse Gases

- Green Houses Gases (GHGs) are used in several gaseous particle detectors due to their characteristics suitable for **optimal detector performance ad long term operation**

- RPCs need to replace $\mathbf{C_2H_2F_4}$ (R134a = TFE) and $\mathbf{SF_6}$ with low Global Warming Potential ecological gases, with unchanged or even better performances

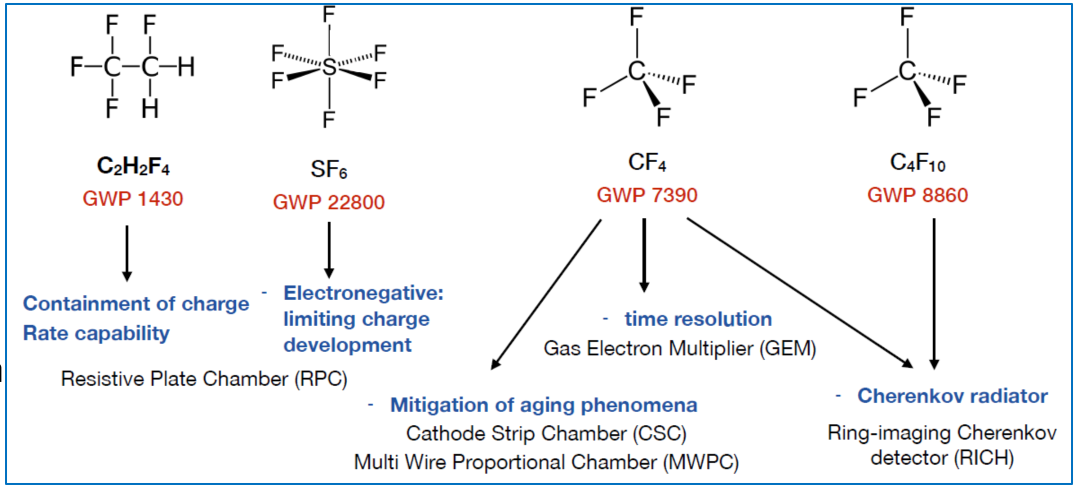
- **Extensive R&D ongoing**

  Some Ecological candidates are already under study

- HEP experiments, present and future, last several (dozens) of year.

A good performance must be maintained for an adequate period

→ Aging tests are needed as well



Gases can also be re-circulated, after purifying them, but only for low leaks system

The RPC EcoGas@GIF++ is a Collaboration **transversal to ALICE, ATLAS, CERN EP-DT, CMS, and LHCb** willing to put together expertise and resources to test potential candidates of eco-friendly gas mixtures with different detectors and electronics and the related aging effect.

MUON SYSTEMS – Wire based detectors – Current State and Application

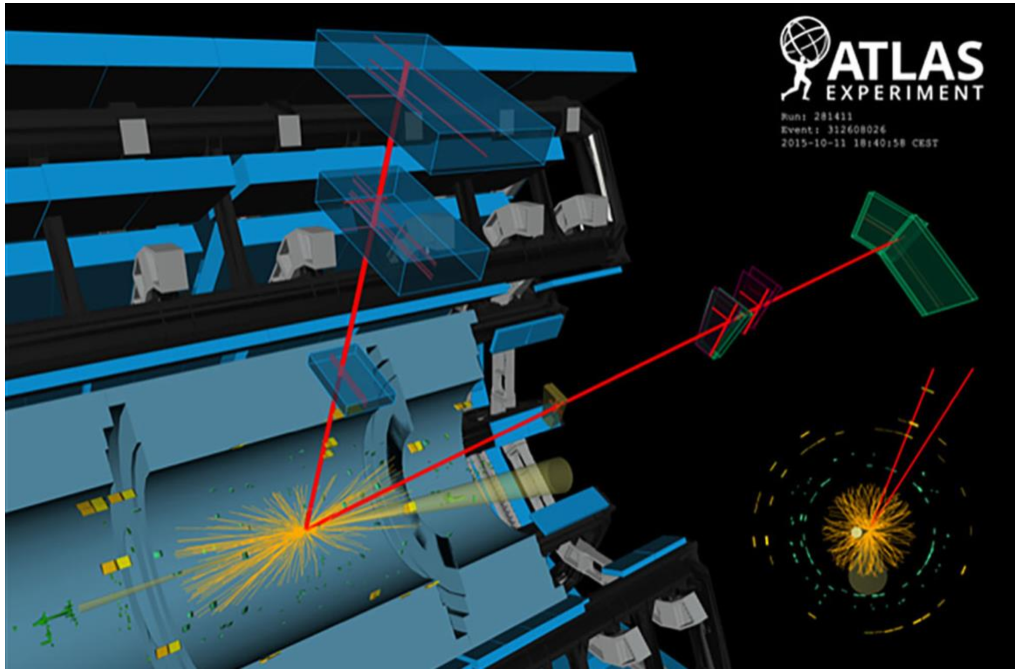
MWPC, TGC, sTGC, CSC, and drift tubes (MDT and DT) are used in the Muon Spectrometers of LHC experiments.

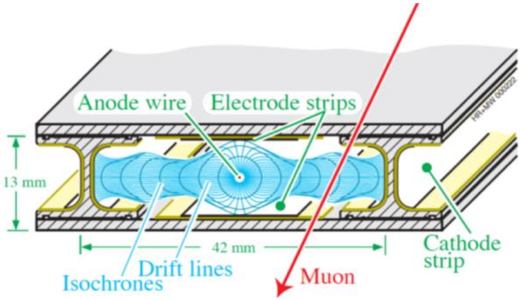
Challenges for Detectors at the LHC (and HL-LHC!!):

- High-rate capability
- Long-term detector longevity (aging effects)
- High spatial granularity
- High time resolution

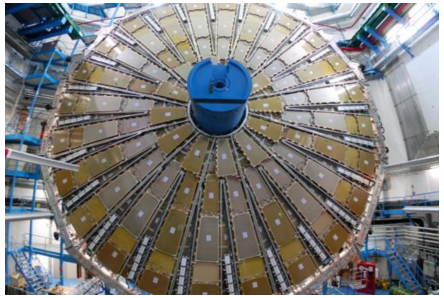
ATLAS and CMS employ different tracking and trigger technologies across various pseudorapidity ranges to adapt to different experimental conditions.

Overall, these detectors have demonstrated stability and reliability.





CMS DT



ATLAS TGC

MUON SYSTEMS – Objectives and Challenges

Primary objective:

Strategically advance R&Ds for ALL TECHNOLOGIES **for new challenges at future facilities.**

- strengthen their stability, robustness, and long-term performance,
- Easy operation and maintenance
- Improve and consolidate construction and quality process
- optimize a cost-effective manufacturing together with industrial partners.

Main Challenges

- Extending the state-of-the-art rate capability up to ~ 1-10 MHz/cm^2 with longevity compatible with decades of operation.

  →advancements in detector resistive configurations, new materials and geometries, low-noise electronics, and fine granularity readout to reduce occupancy.

- Addressing low/medium-rate applications involving muon tracking in HEP experiments like at FCCee, and exploring applications beyond HEP for large areas
- Reliable and efficient operation with low-GWP (Global Warming Potential) gas mixtures.
- Spatial resolution ~100 um
- Improving time resolution at the level of nanosecond and achieving resolutions up to 10-100 ps for applications in high-rate collider experiments to mitigate pile-up effects.
- Establishing large-scale serial production and cost reduction measures.

INNER AND CENTRAL TRACKING

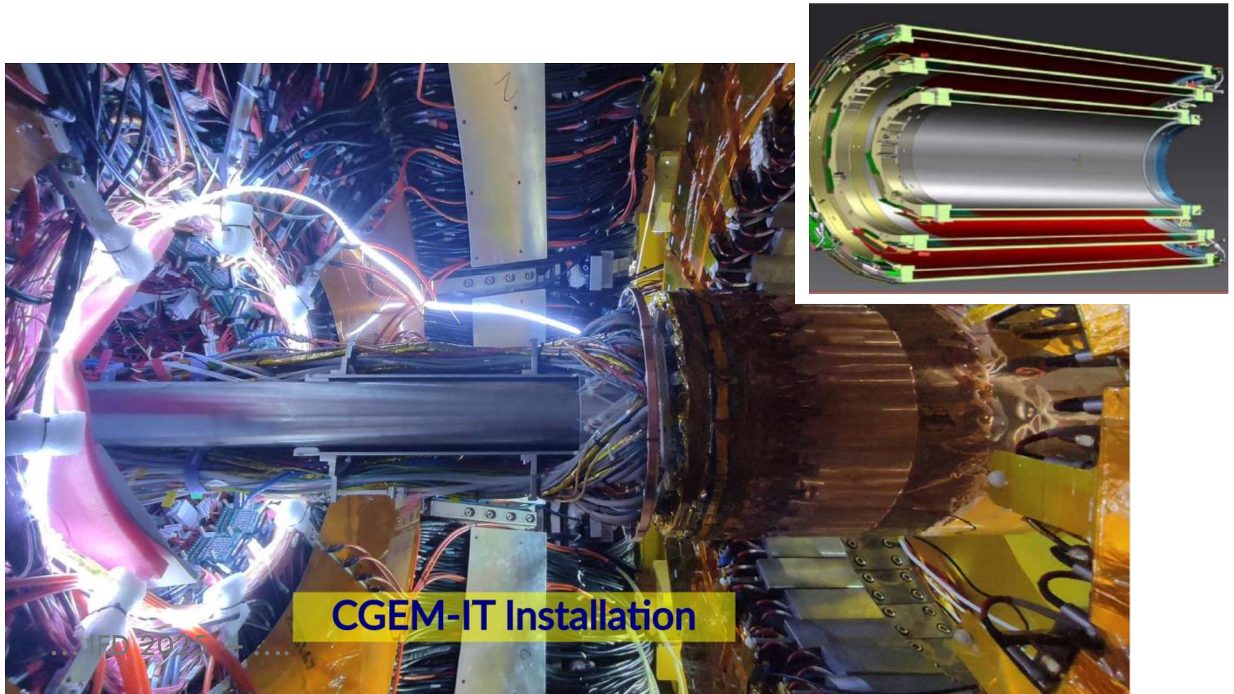
- MPGD
- DRIFT CHAMBERS
- STRAW AND DRIFT TUBE CHAMBERS (…not in this presentation)
- TPC

INNER AND CENTRAL TRACKING – MPGD

Cylindrical GEM – An example:

C-GEM at BES-III

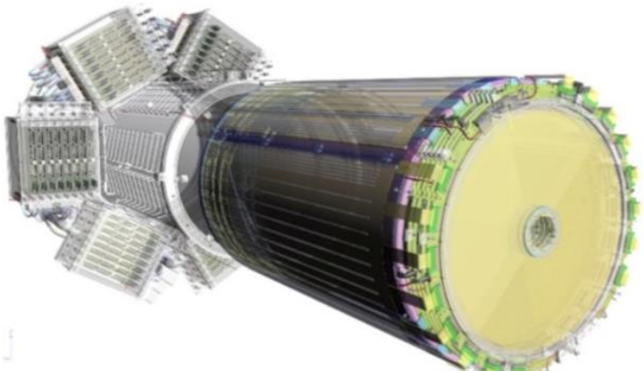
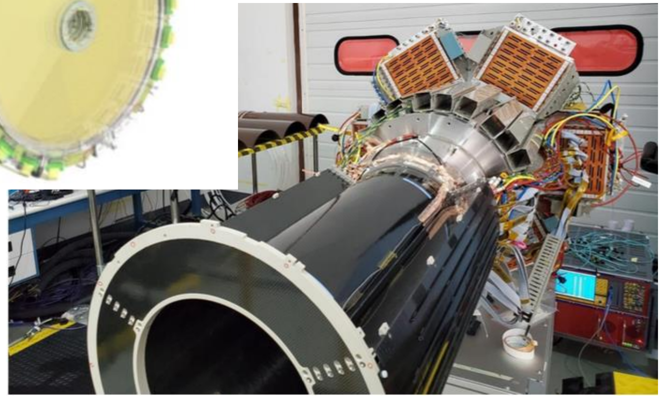
- three layers of cylindrical triple-GEM
- spatial resolution: <300 um, ~150 um azimuthal
- rate capability, and radiation hardness
- momentum resolution: 0.5% at 1 GeV/c
- 0.5% X0 per layer material budget



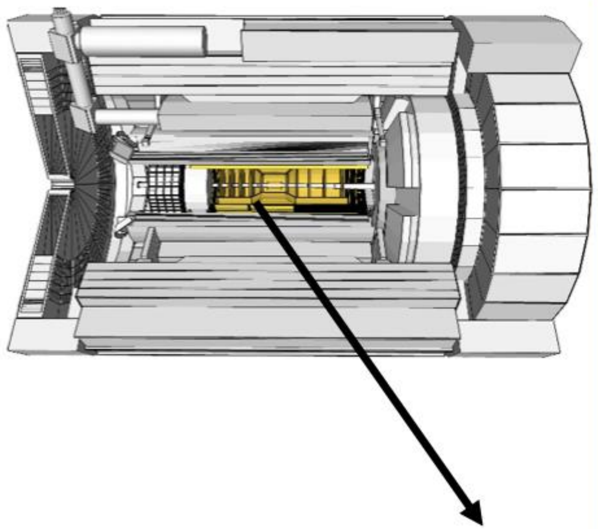
Cylindrical MICROMEGAS – An example:

Micromegas Vertex Tracker for CLAS12 at JLab

- Taking data since 2017
- Challenging environment: B = 5 T – High flux / High integrated current (several Coulombs)
- 2.9 m^2 / 6 layers / drift gap 3 mm / X_0 ~ 0.33/layer
- Six layers – drift gap 3 mm
- Gas: Argon95% - Isobutane 5%

INNER AND CENTRAL TRACKING – Proposal for ePIC @ EIC

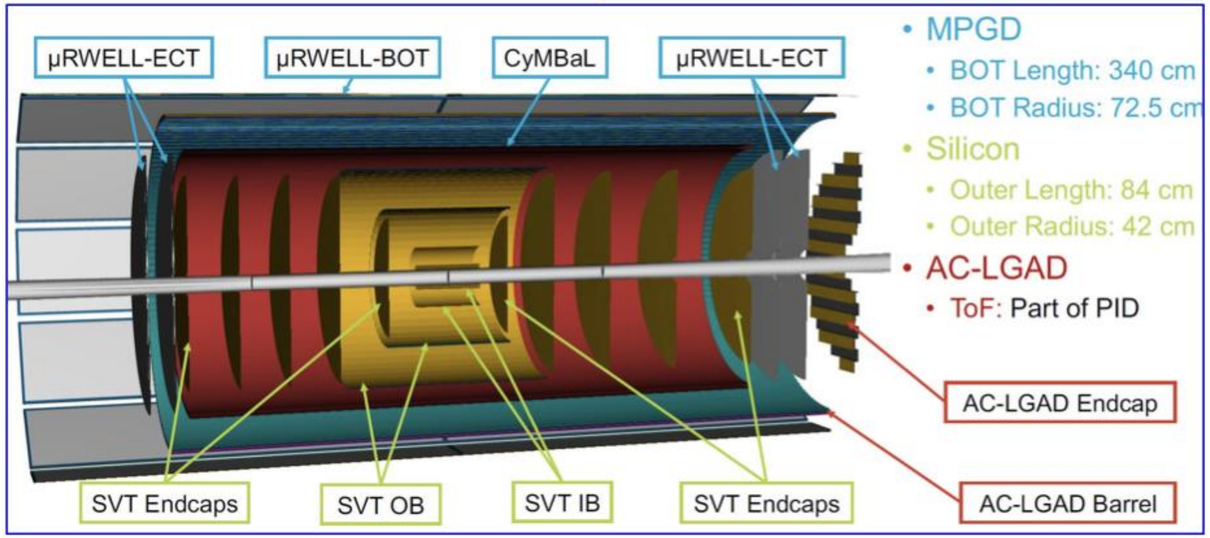


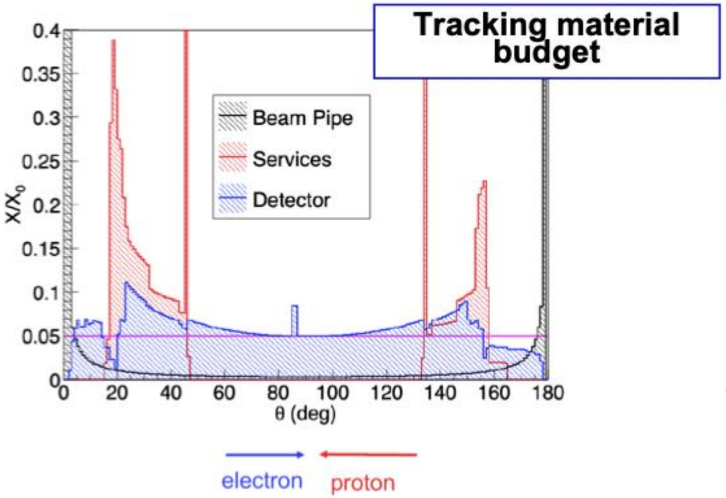
Complementary tracking technologies characterized by light materials

SVT: Si trackers based on ALICE ITS3 65 nm MAPS sensors
- **Fine space resolution < 20 μm**
- **Five cylindrical layers in the barrel and five disks in each endcap**

MPGD trackers
- **Good time resolution $\mathcal{O}$(10 ns)**
- **Cylindrical MICROMEGAS**
- **Planar μR-WELL with GEM pre-amplification**

Additional information
- AC-LGADs for ToF (PID) - very fine time resolution: 20/30 ps
- First layer of the barrel imaging EM calorimeter – fine space resolution (150 μm), good time resolution (~ 2 ns)

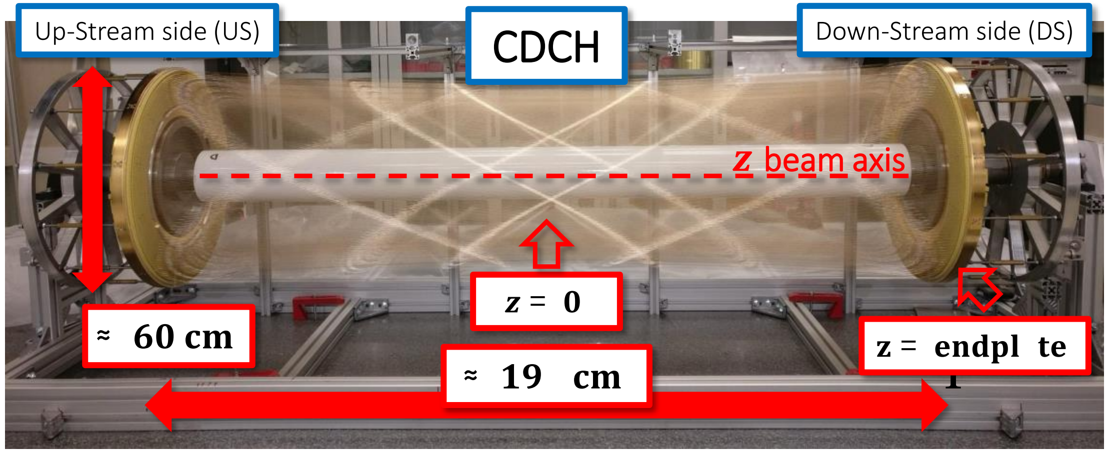


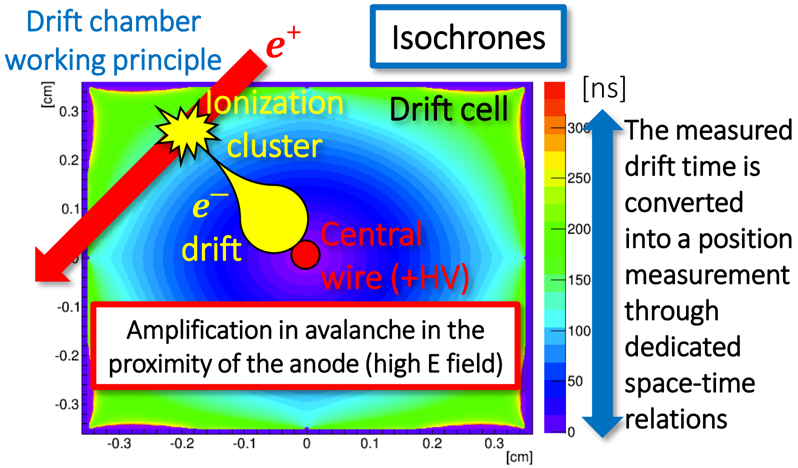


From S. Dalla Torre MPGD2024, Hefei 14-18 October 2024

MEG II drift chamber

Detector performance





e^+ variable	MEG	MEG II
ΔE_e (keV)	380	91
$\Delta\theta_e, \Delta\varphi_e$ (mrad)	9.4, 8.7	7.2, 4.1
$\Delta Z, \Delta Y$ (at target, mm)	2.4, 1.2	2.0, 0.7
$\varepsilon_{trackin} \times \varepsilon_{TC-gmatch}$ (%)	65 ≺45	74 ≺91

- Currently most updated reconstruction algorithms on real data
- Practically at the MC level

- Low-mass single volume detector with high granularity filled with He:iC_4H_{10} 90:10 gas mixture
  - + additives to improve the operational stability: 1.5% isopropyl alcohol + 0.5% Oxygen
  - 9 concentric layers of 192 drift cells defined by 11904 wires
  - Small cells few mm wide [illegible] MHz/cell (center) near the stopping target
  - High density of sensitive elements: ≺4 hits more than MEG drift chamber (DCH)
- Total radiation length 1.5×10^{-3} X_0: less than 2×10^{-3} X_0 of MEG DCH or 150 µm of Silicon
  - MCS minimization and γ background reduction (bremsstrahlung and Annihilation-In-Flight)
- Single-hit resolution (measured on prototypes): $\sigma_{hit} < 120$ µm
- Extremely high wires density (12 wires/cm^2) → the classical technique with wires anchored to endplates with feedthroughs is hard to implement
  - CDCH is the first drift chamber ever designed and built in a modular way

3/45

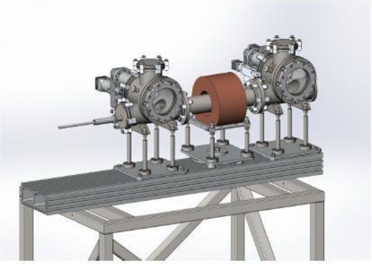
Challenges for large-volume drift chambers

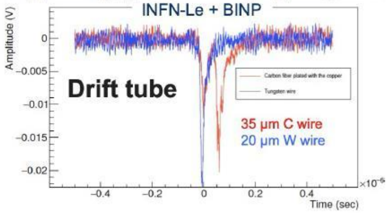
λ = linear charge density (gas gain) L = wire length, r_w wire radius, w = drift cell width YTS = wire material yield strength

- **Electrostatic stability** condition: $\frac{\lambda^2}{4\pi\varepsilon}\frac{L^2}{w^2} < wire\ tension < YTS \cdot \pi r_w^2$

  The proposed drift chambers for FCC-ee and CEPC have lengths **L = 4 m** and plan to exploit the cluster counting technique, which requires gas gains **~5×10^5**.
  This poses serious constraints on the drift cell width (**w**) and on the wire material (**YTS**).

  ⇒ new wire material studies



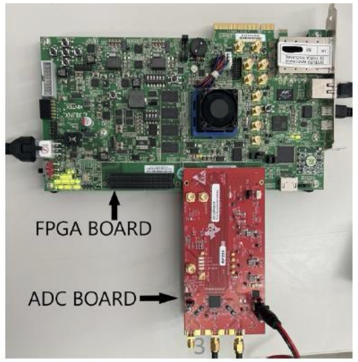


- **Non-flammable gas / recirculating gas systems**
  Safety requirements (**ATEX**) demands stringent limitations on flammable gases;
  Continuous increase of **noble gases cost**

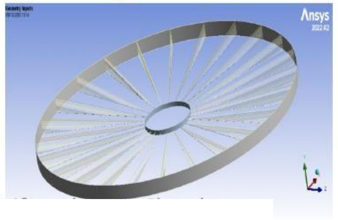
  ⇒ gas studies

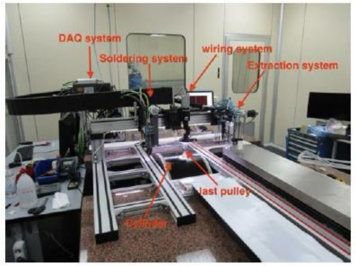
- **Data throughput**
  Large number of channels, high signal sampling rate, long drift times (slow drift velocity), required for cluster counting, and high physics trigger rate (Z_0-pole at FCC-ee) imply data transfer rates in excess of ~**1 TB/s**

  ⇒ on-line real time data reduction algorithms



- **New wiring systems for high granularities / / new end-plates / new materials**
  - reduction of the material budget





- Assessment of the **Cluster Counting/Timing technique** with real data and simulation

Mechanical structure with FEM for IDEA DCH

Big Problems to manage!

- σ_{xy} < **100 µm** → accuracy on the position of the anodic wires < **50 µm**.
- The anodic and cathodic wires should be parallel in space to preserve the constant electric field.
- A 20 µm tungsten wire, 4 m long, will bow about 400 µm at its middle point, if tensioned with a load of approximately 30 grams.

30 gr tension for each wire → **10 tonnes** of total load on the **endcap**

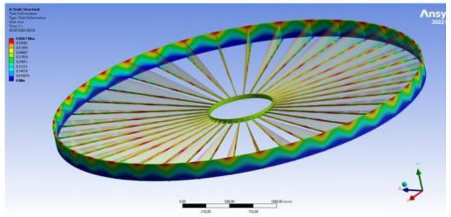
Load on spokes (24 sectors): 416 Kg/spoke => 2.5 Kg/cm average

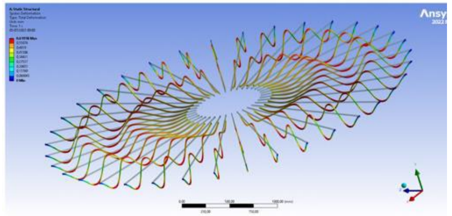
Load on stays (14 stays/spoke) - 416 Kg/14/sin 8.6° = 200 Kg/stay

Goal: minimizing the deformation of the spokes using prestressing force in the cables

Total deformation (mm) of the drift chamber with the edge of the outer cylinders fixed			
No prestress		Prestress in the cables	
Spokes	Outer cylinder	Spokes	Outer cylinder
14.099	0.63	0.62	0.67

The structure exhibited a deformation of 600 µm but our goal was to limit the deformation of the spokes to 200 µm while ensuring the structural integrity.

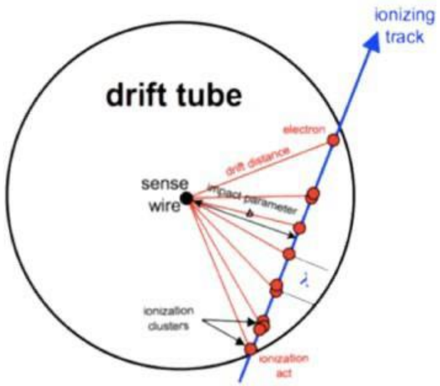


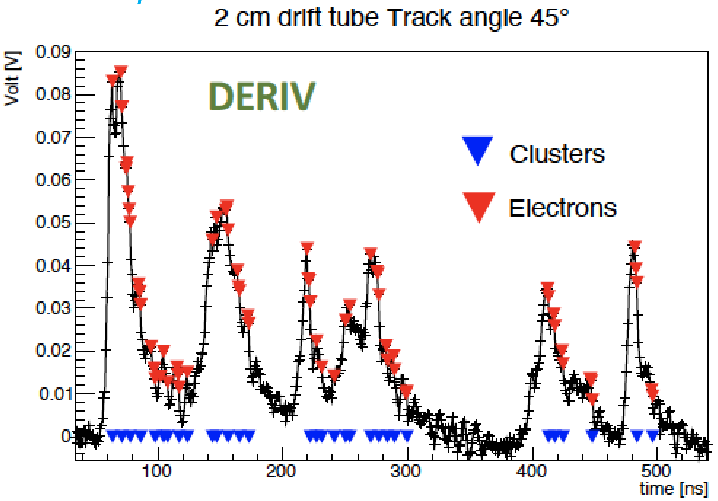


The Drift Chamber: Cluster Counting/Timing and PID

Principle: In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.





- collect signal and identify peaks
- record the time of arrival of electrons generated in every ionisation cluster
- reconstruct the trajectory at the most likely position

Requirements
fast front-end electronics
(**bandwidth ~ 1 GHz**)
high sampling rate digitization
(**~ 2 GSa/s, 12 bits, >3 KB**)

- Landau distribution of dE/dx originated by the mixing of primary and secondary ionizations, has large fluctuations and limits separation power of PID primary ionization is a Poisson process, has small fluctuations

- The cluster counting is based on replacing the measurement of an ANALOG information (the [truncated] mean dE/dX) with a DIGITAL one, the number of ionisation clusters per unit length:

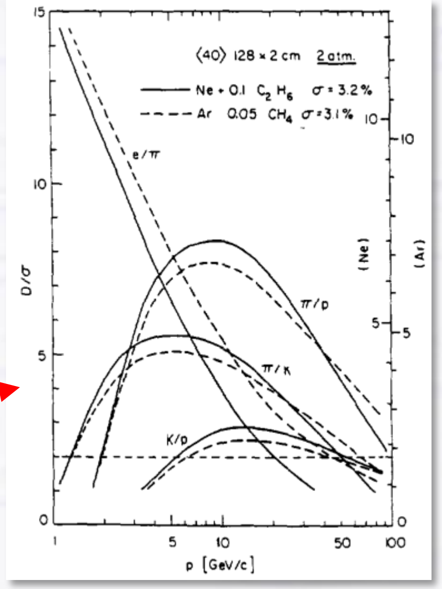
dE/dx: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx$ 4.3%

dN_{cl}/dx: for He/iC_4H_{10}=90/10 and a 2m track gives $\sigma_{dNcl/dx}$ **$/(dN_{cl}/dx)$** < 2.0%

Cluster Counting

Cluster Counting

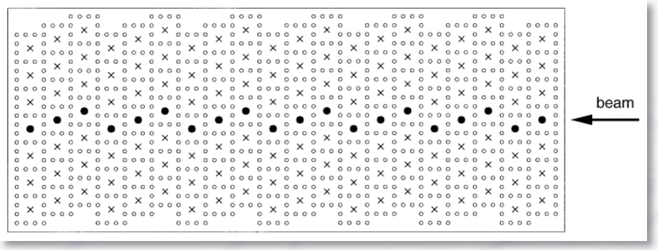
- Direct cluster counting would avoid any problems with cluster fluctuations, truncated mean etc.
  - no charge measurement need, just counting
- In theory → ultimate way to measure dE/dx
  - 30 clusters/cm * 100 cm track length = 3000 clusters
  - 1.8% dE/dx resolution by cluster counting (statistical error only)
  - 5.4% dE/dx resolution by charge measurement (Lehraus fit)
- Not a brand new idea
  - first ideas (1969) by A. Davidenko et al. (JETP, 1969, Vol. 28, No. 2, p. 223)
  - Detailed studies in mid-1990s by G. Malamud, A. Breskin, B. Chechik
    - cluster statistics
    - measurements in low pressure drift chamber
    - simulations
    - expected particle separation



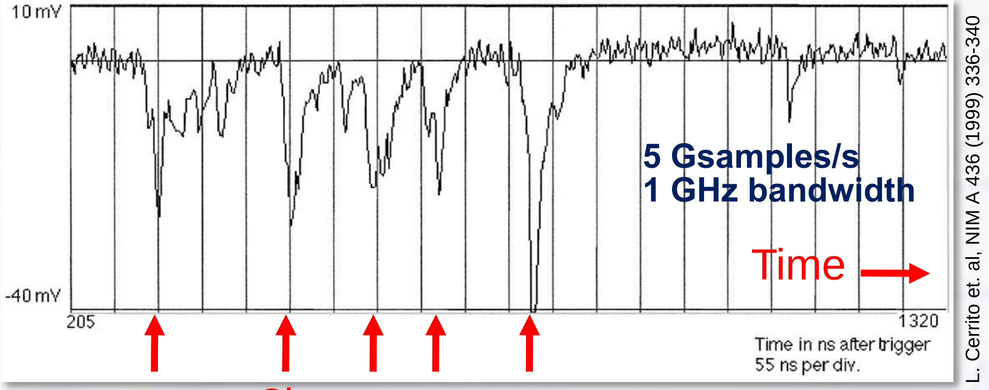
G. Malamud, A. Breskin, B. Chechik, NIM A 372 (1996) 19-30

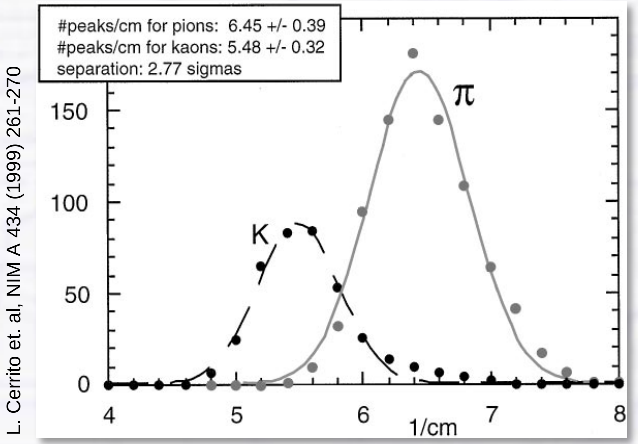
Cluster Counting (by time)

- Test beam measurements 1998 using He/CH_4 (80/20)



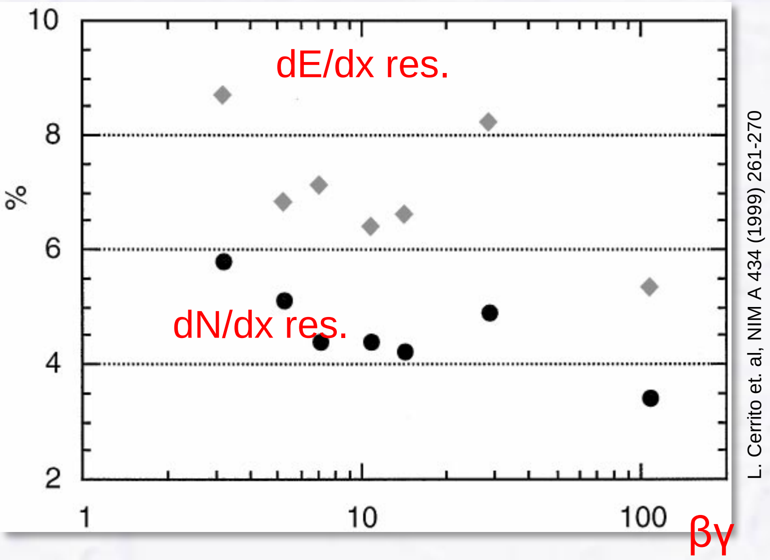
drift cells





3 GeV/c

120 cm track length

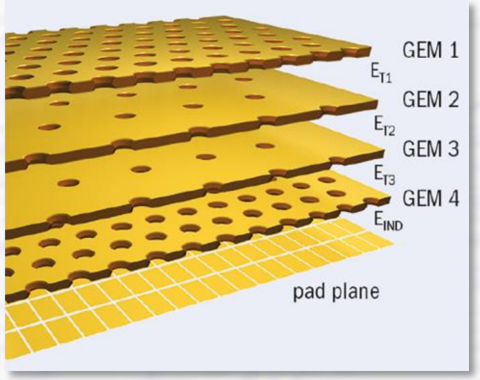


- Cluster Counting works in test beam under controlled conditions
- but not yet used in large scale particle detectors

TPC with Cluster Counting

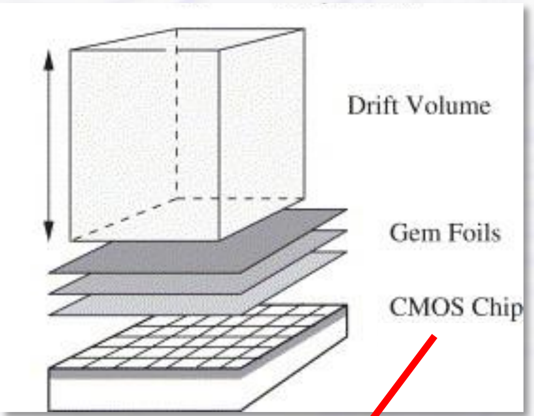
- **Different endplate technologies suitable for Cluster Counting**

Multiple-GEMs with conventional (passive) pads

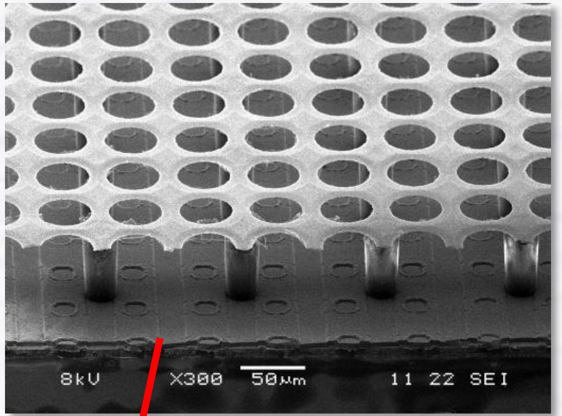


ALICE TPC-upgrade + ILD TPC

Multiple-GEMs with TimePix (active pads, 55 x 55 μm^2)



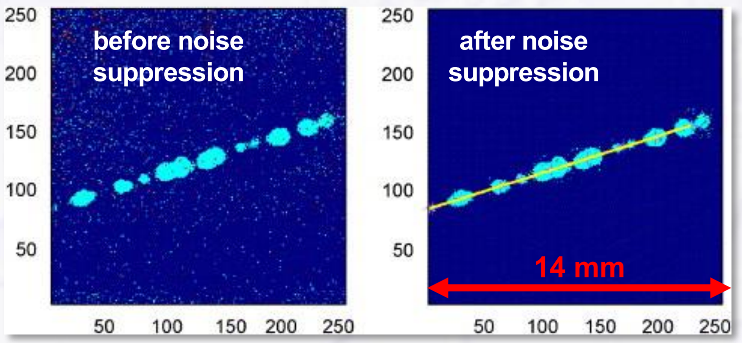
InGrid / GridPix = MicroMegas on top of TimePix (active pads, 55 x 55 μm^2)



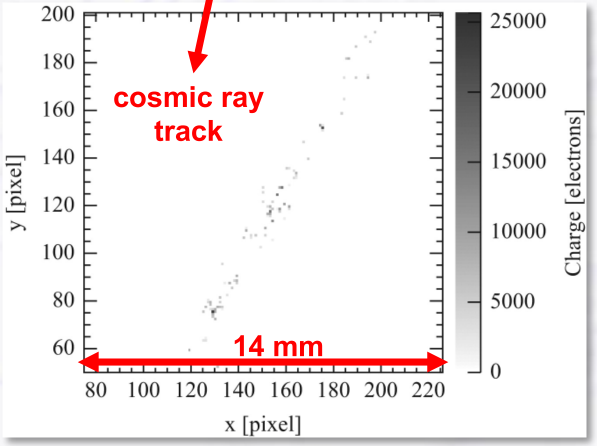
- **Visible individual clusters**

electron track from ^{106}Ru source in Ar/CO_2 (70/30)

“blobs” due to diffusion in GEM stack



A. Bamberger et al, NIM A 573 (2007), 361-370



C. Krieger et al, NIM A 729 (2013), 905-909

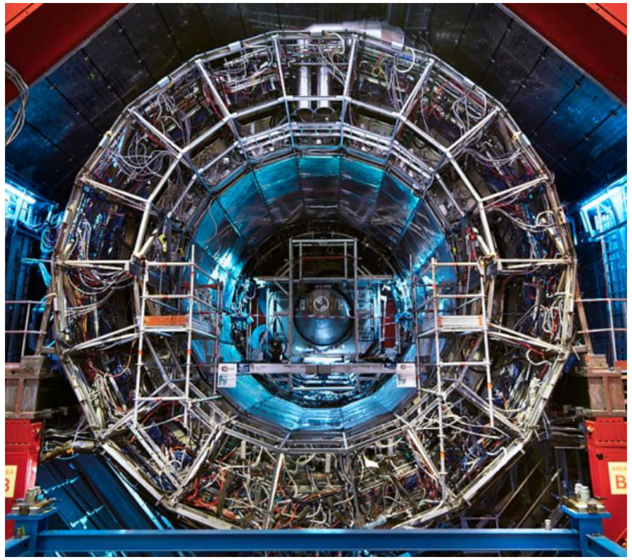
TPC
Trackers, Decay chambers, Beyond HEP

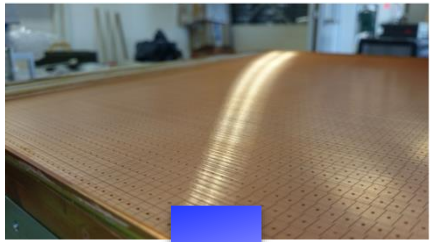
The quintessential TPC you all know and love: ALICE

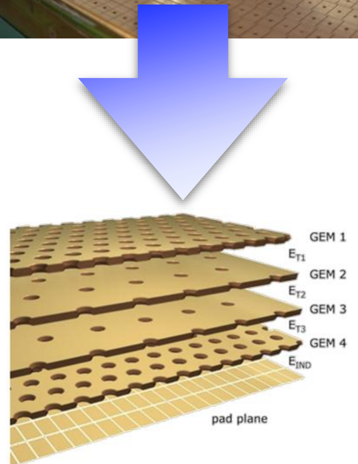
ALICE upgrade challenges to solve while preserving momentum resolution and PID with dE/dx:

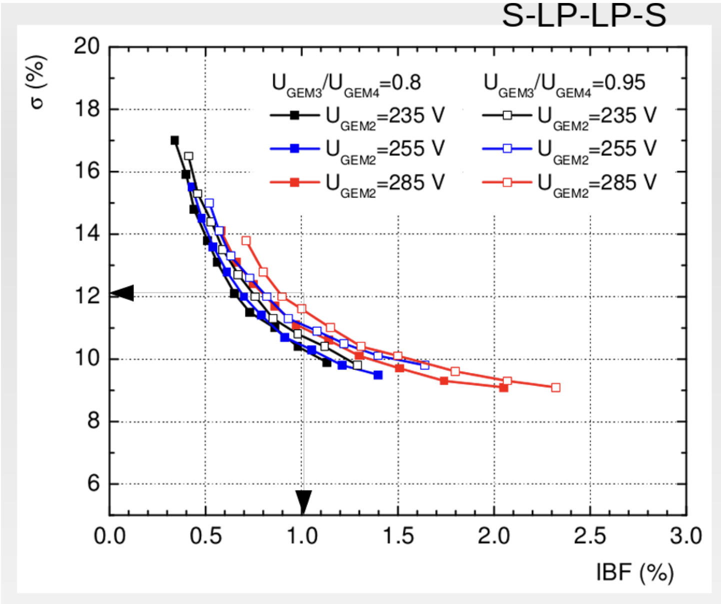
- **Increased rate**
  - solved with continuous readout scheme
  - do not allow gating
- **Increased ion backflow**
  - solved with 4 GEM stack instead of MWPC
- **Increased discharge probabilities**
  - solved with GEMs + Active Voltage Divider

- **BUT ALICE upgrade just happened….what's next?**
  - **no TPC foreseen for ALICE3…**

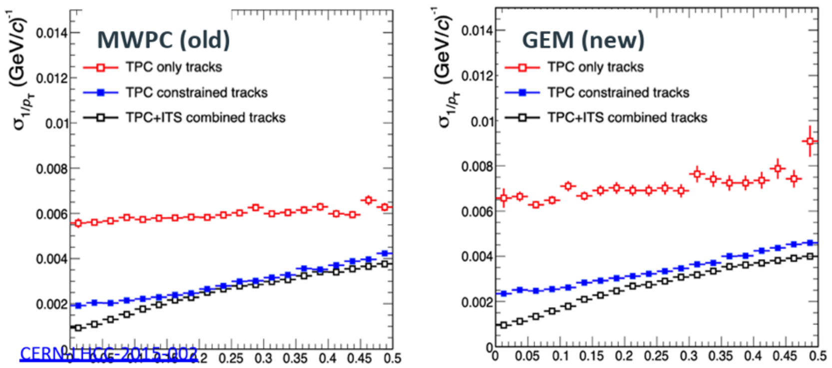








Momentum resolution vs p_T



GEM TPC

- **Preserve momentum resolution for TPC+ITS tracks**
- **Preserve particle identification (d*E*/d*x*)**

A possible future for TPC @ colliders: the ILD TPC @ ILC

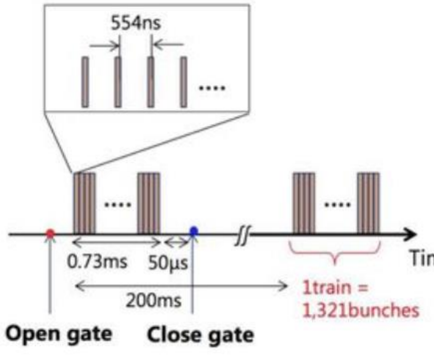
ILD TPC challenges

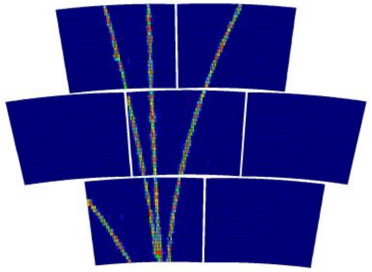
- **Single point resolution 100 um over entire drift length**
  - Readout scheme optimisation
- **Increased ion backflow**
  - use large aperture GEM instead of wires for the gating
  - INGRID pixel scheme might not require gating
- **Mechanics/calibration/alignment**
  - require novel solutions
- **Large beam background**
  - optimise gas to minimise interaction with photons (Ne?)

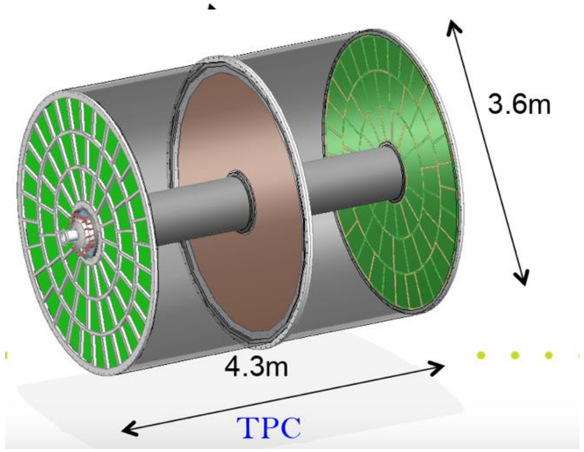
TPC Requirements: *

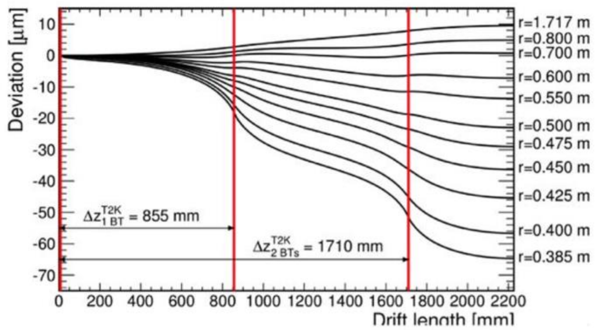
- **Momentum resolution:**
  $\delta(1/p_T) < 9\times10^{-5}\ \mathrm{GeV}^{-1}$
- **Single hit resolution 3.5T:**
  $\sigma(r\phi) < 100\ \mu m$
  $\sigma(z) < 500\ \mu m$
- **Tracking eff.** for $p_T > 1$ GeV: $> 97\%$
- **dE/dx resolution** $\sim 5\%$

At the ILC, the bunch trains last about 1ms every 200 ms, giving rise to ion disks slowly drifting to the cathode









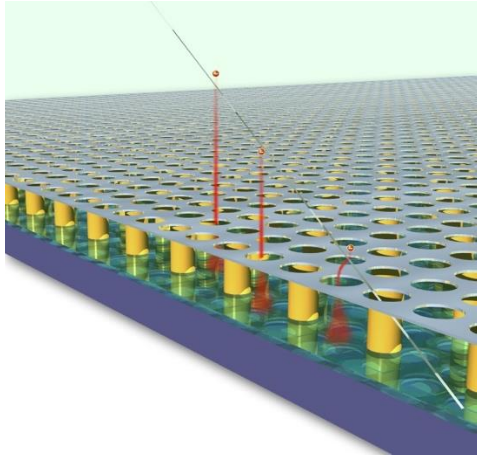
*might not be the most updated, not many ILC detector papers in the last years…

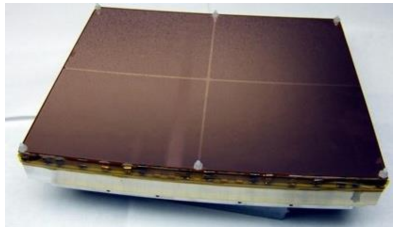
After 2 disks, the electrons receive a kick of up to 60 μm, too much wrt the systematics

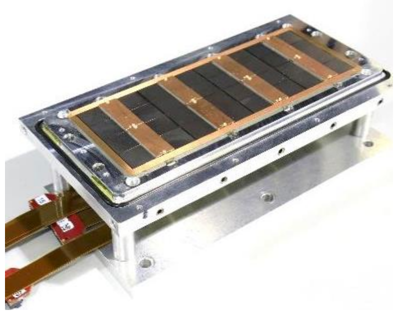
(Personal biased) ILD TPC preferred solution: GridPix readout scheme

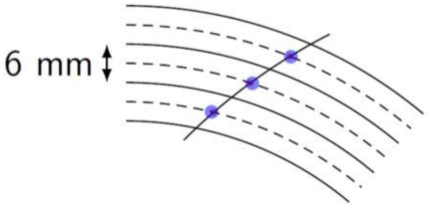
Motivation for a pixelised TPC

- Improved dE/dx by cluster counting
- Improved measurement of low angle tracks
- Improved double track separation
- Much reduced hodoscope effect
- Lower occupancy in high rate environments
- Fully digital read out
- **Can enable cluster counting for improved dE/dx**
- **Can reduce IBF**

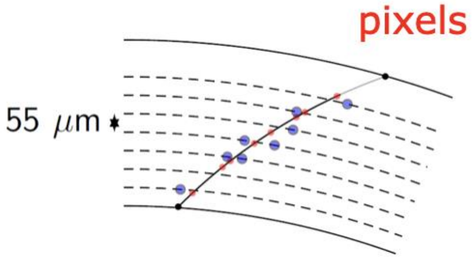








22 electrons / hit
~ 200 hits / track



1 electron / hit
~ 10 000 hits / track

GridPix concept

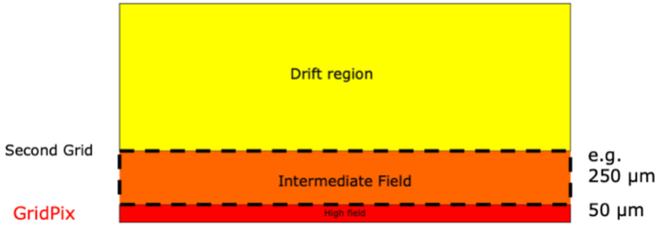
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability

8-quad GridPix modules tracking precision measured with testbeam at DESY (no B field, going to improve when added):

- position 9 μm (xy) 13 μm (z)
- angle 0.19 mrad (dx/dy) 0.25 (dz/dy) mrad
- module tracklength = 157.96 mm

Ion Gating with GridPix

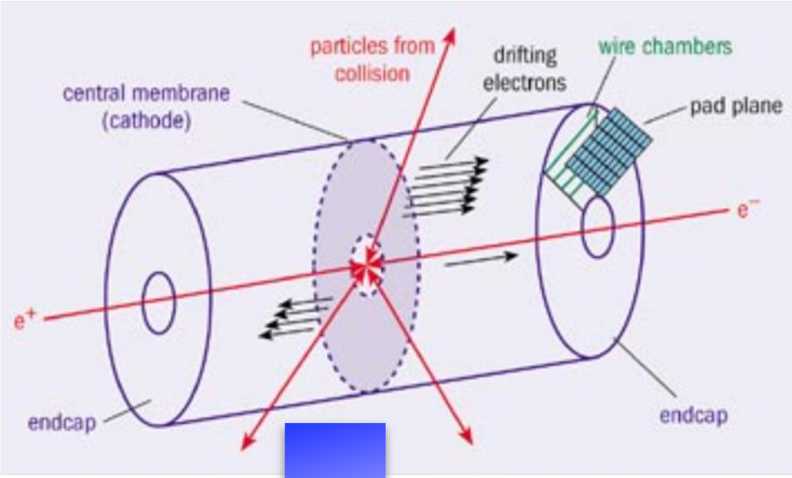
- The idea is that by creating two field regions, one with a medium field and one with a high field (our standard Grid Pix) one could reduce the ion backflow in two stages.

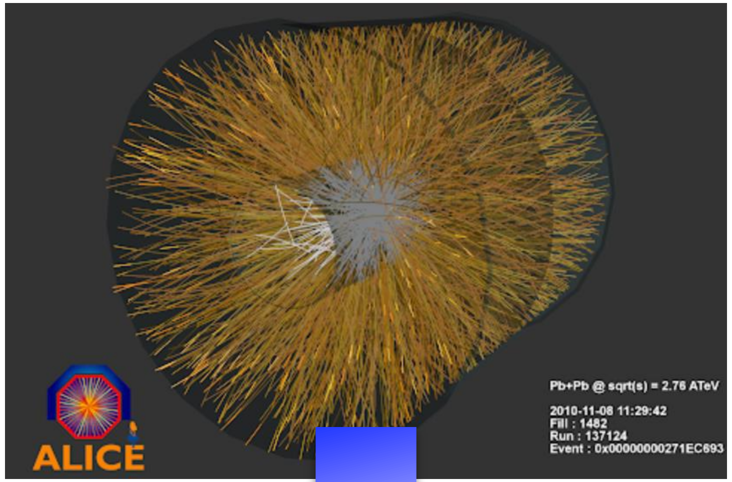


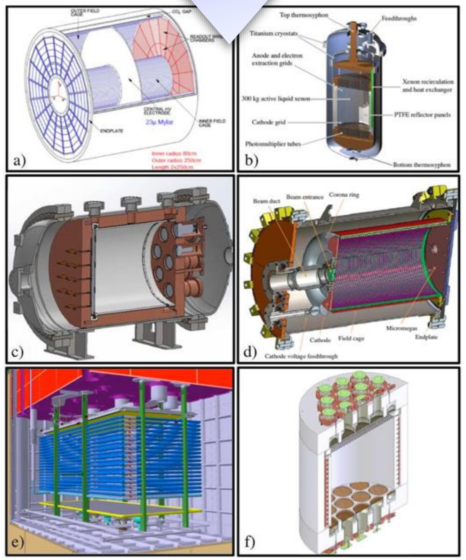
Ion backflow	Hole 30 μm	Hole 25 μm	Hole 20 μm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	12 10^{-4}	3 10^{-4}	1 10^{-4}
transparancy	100%	99.4%	91.7%

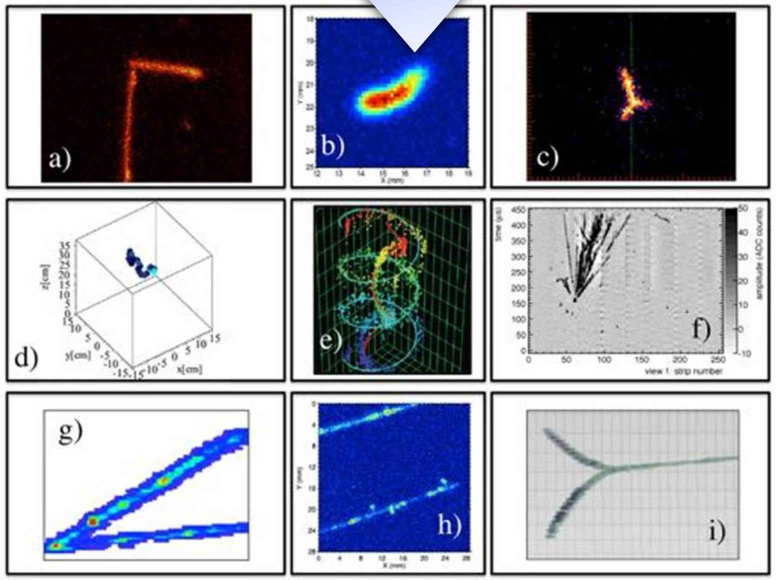
In order to reach IBF*Gain (2 10^3) below one has to choose a slightly smaller hole size of 25 or 20 microns.

TPC: not only an HEP detector, recent change of paradigm









New paradigms:

- No just a tracker, but **an experiment**
- TPC as active target
- No t_0
- No magnetic field
- No aging
- No rate issues
- Natural backgrounds issue require **low radioactivity materials**
- **Much lower energy** ROI
- Much **more complex topology**
- Total energy measured —>full event containment
- Not MIP: PID through topology or **differential dE/dx** require very high granularity
- **Precise topology can grant positive claim (or background free measurement)**

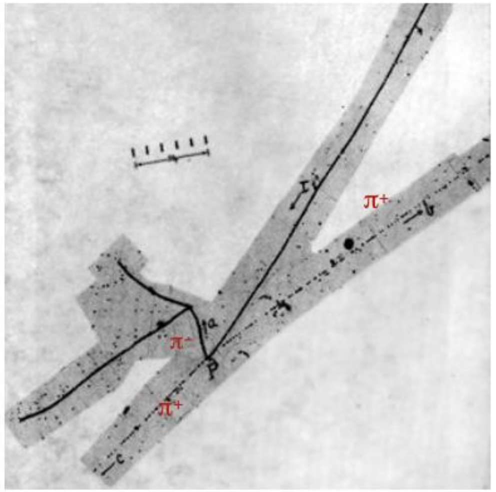
TPCs for rare events searches: a modern full imaging detector

Photographic emulsions

Cecil Frank Powell
Nobel Laureate 1950

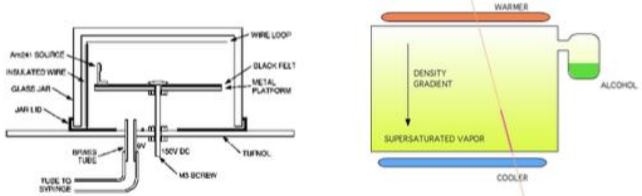
DISCOVERY OF THE τ (K⁺) *Brown et al, 1948*

$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$



Cloud chamber

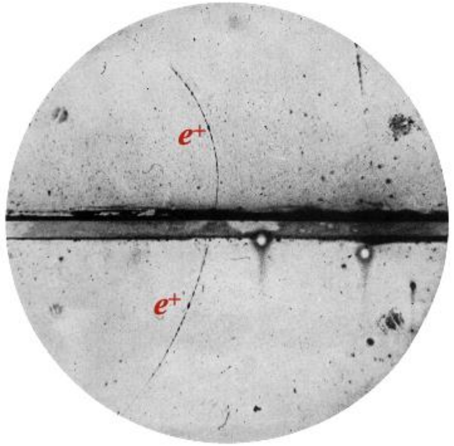
Expansion Diffusion



Charles Thompson Wilson (1911)

C. T. Wilson, A. Compton, Nobel Laureates 1927

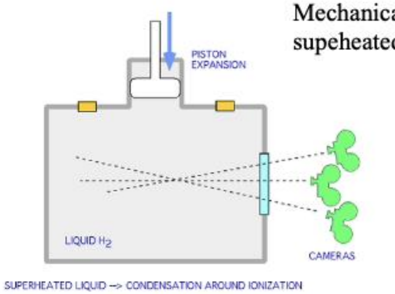
DISCOVERY OF THE POSITRON



A COSMICCHARGED PARTICLE (1) ENTERS THE DETECTOR, LOSES ENERGY IN A METAL PLATE AND CONTINUES WITH LOWER ENERGY (2). THE CURVATURE IN MAGNETIC FIELD IDENTIFIES ITS SIGN AND MASS.

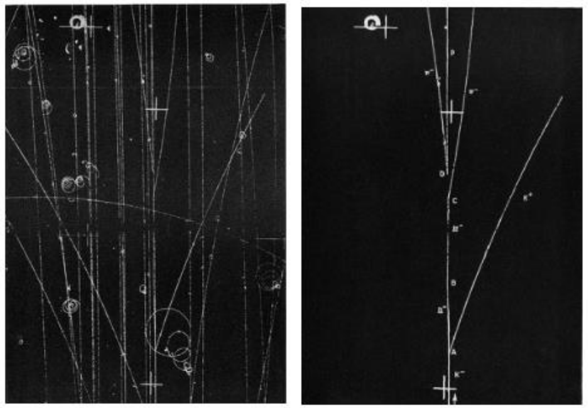
Carl Davis Anderson. Nobel Laureate 1936

Bubble chamber



Mechanical expansion of supeheated liquid (H_2)

Donald Arthur Glaser
Nobel Laureate 1960



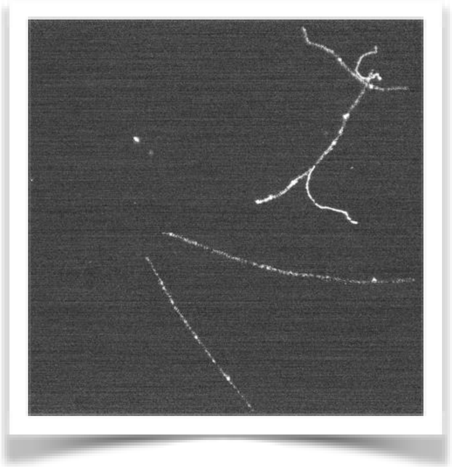
$K^- + p \rightarrow K^+ + \Omega^- + K^0$
$\hookrightarrow \Xi^- + \pi^0$
$\hookrightarrow \Lambda + \pi^-$
$\hookrightarrow p + \pi^-$

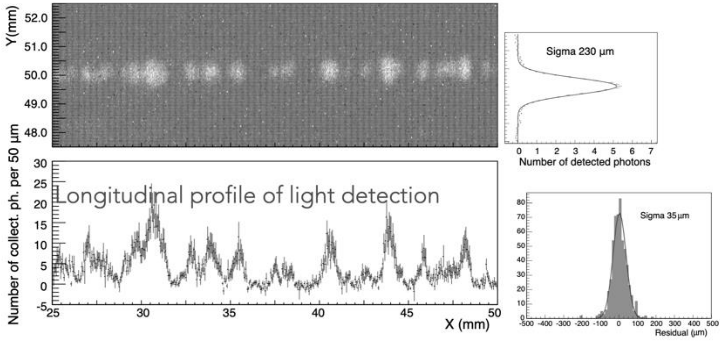
TPC for rare events searches: experimental technique advantages and "enemies"

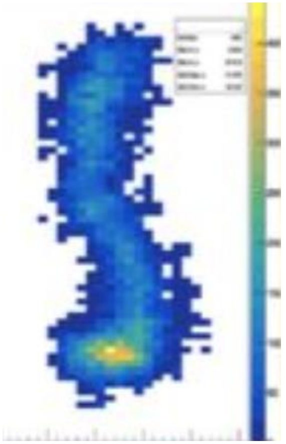
Topology advantages:
- Physics case **signature identification**
- Direction
- Impact point
- Straight vs curly tracks: momentum and PID

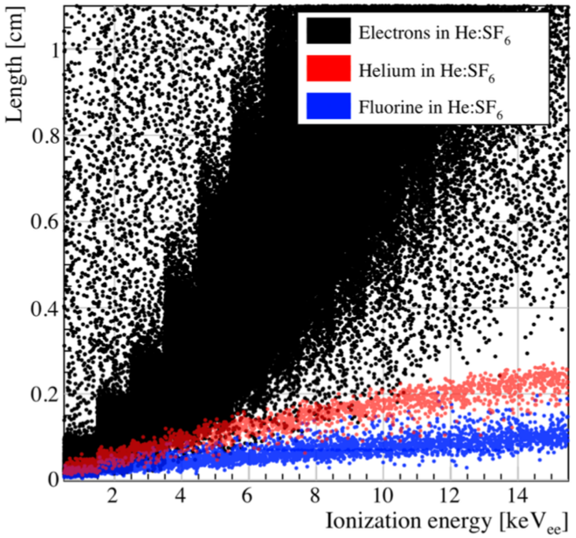
Differential dE/dx:
- Sense (i.e. vector)
- Direction
- PID
- Cluster counting

Combination of event variables:
- Physics case **signature identification**
- Range vs energy —> PID
- Topology variables —> PID





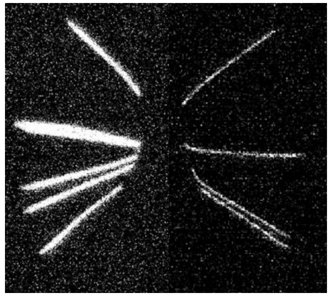


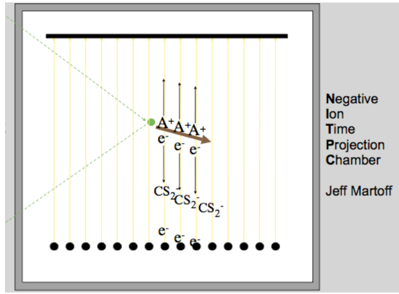


Enemies
- Multiple scattering
- Straggling
- Diffusion
- Insufficient segmentation/too large point spread function
- Signal/noise per sensor
- Light collection and single photon sensitivity for optical readout

TPC for rare events searches: gas features and “enemies”

$$\mathcal{N}_e(x',y',z') = \frac{e^{-\frac{1}{2}\left(\frac{x'-x}{D_T^*\sqrt{z}}\right)^2} e^{-\frac{1}{2}\left(\frac{y'-y}{D_T^*\sqrt{z}}\right)^2} e^{-\frac{1}{2}\left(\frac{z'}{D_L^*\sqrt{z}}\right)^2}}{(2\pi D_T^{*,2} z)(2\pi D_L^{*,2} z)^{1/2}} \times \bar{n}_e \cdot e^{-\eta z} \quad (26)$$





Attachment during drift
- Spoils gain
- Need high purity level
- Can be reduced increasing drift velocity

Diffusion
- Spoils tracks topology
- Need to minimise the energy of the drifting charge

Charge arrival time at the multiplication plane
- Grant track reconstruction along drift direction
- Drift velocity determines electronics buffer size and sampling frequency and resolution along Z

Current/novel lines of development related to gas:
- “Cold” gases, low density gases, Negative Ion Drift
- Eco-friendly without affecting other features
- Enhance gain towards lower thresholds without inducing saturation
- Enhance LY for optical readouts
- Extend dynamic range (simultaneous low energy ER and NR precise measurement)
- Improve gas systems gas thightness, recirculation and purification capabilities
- Reduce/find alternatives for material outgassing
- Go beyond gas mixtures “black magic”: develop simulation of microscopic gas properties to find/predict their macroscopic features

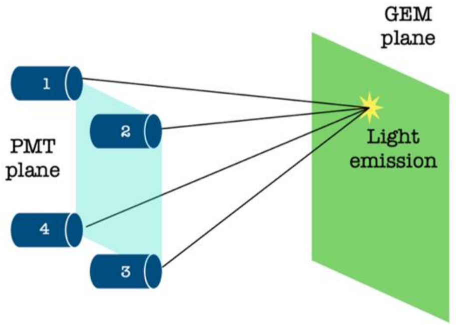
TPC for rare events searches: readout scheme advantages and “enemies”

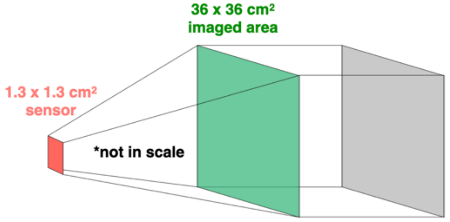
Charge amplification & collection

- multiplication factor and readout segmentation determine sensitivity and spatial precision
- aim at high gain without saturation
- electronics tailored on charge time arrival (depending on v_{drift})

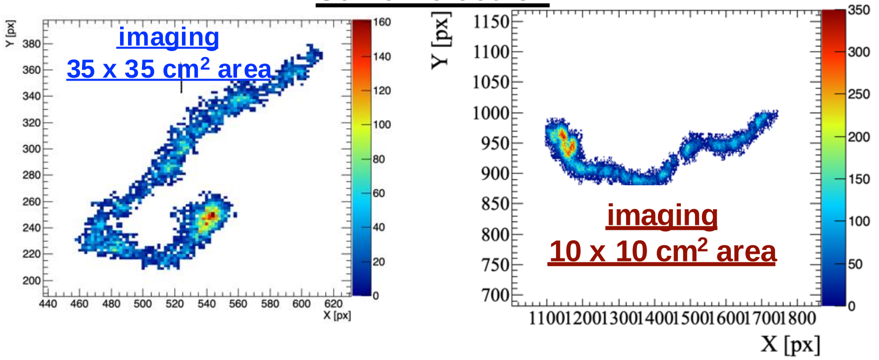
Light collection

- coverage is the problem
  - use reflectors if (high) granularity is not an issue (PMT, SiPM)
  - alternatively, CCD/CMOS coupled to fast lens…but
    - $10^{-3/-4}$ LY reduction
    - LY radial dependence and image distortion





30 keV electron

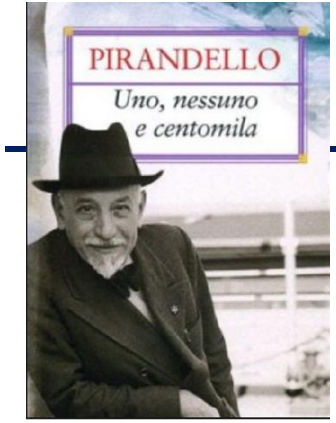


Current/novel lines of development to improve readout scheme:

- Dedicated MPGD development for improved granularity and reduced IBF
- Dedicated MPGD development for NID operation
- Dedicated MPGD development to enhance signal per segmentation area
- Innovative combined readout approaches (optical PMT + CMOS, mixed optical + charge ‘a la Migdal’…)
- Improve optical readout through:
  - new lens concept to increase aperture, reduced focal length, vignetting and barreling
  - new photon detector concept/strategies

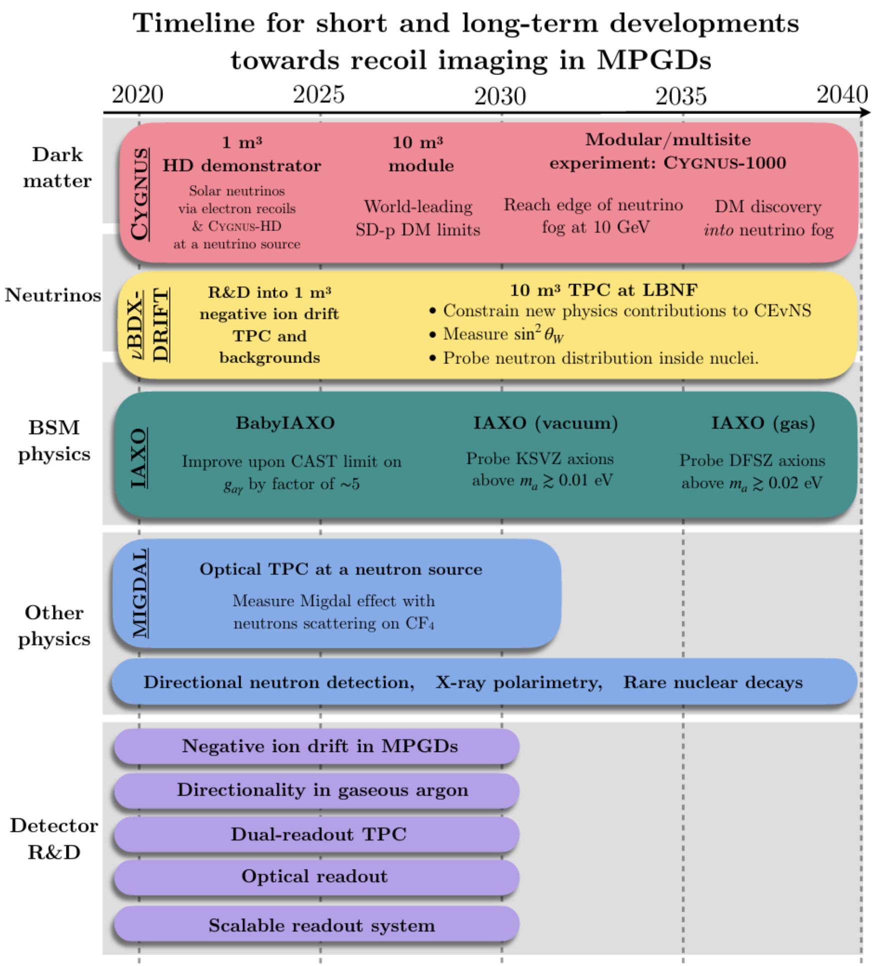
NOTE: Radiopurity

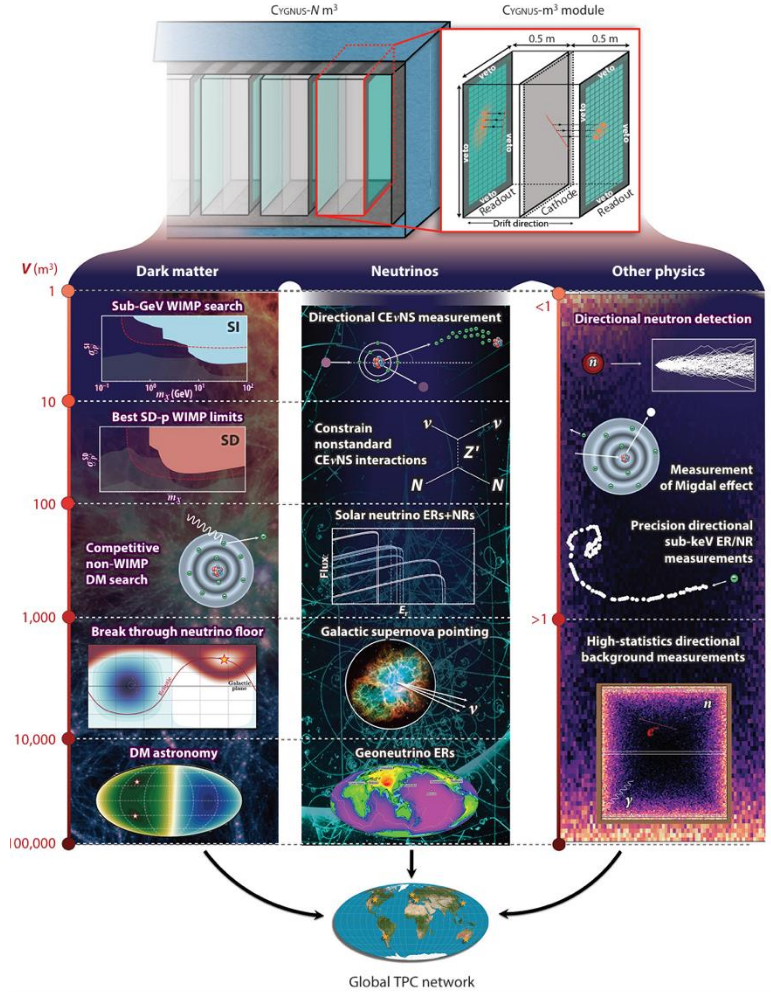
- **needed (mainly) for components in contact with active volume, i.e. amplification & field cage**
- **needed for charge readouts**
- **less stringent for optical readout located outside the active volume**



One, no one and one hundred thousand (imaging) TPC applications beyond HEP

- Directional DM searches
- Low mass DM searches
- CEvNS
- X-ray polarimetry
- Neutrinoless double beta decay searches
- Near detector for neutrino oscillation
- Solar & Supernovae neutrinos
- Dark sector at fixed target
- Migdal effect search
- Rare nuclear decays
- High precision neutrons detection
- Solar axions
- .....**T**o **B**e **D**eveloped ;)





List of contributions

This list only partially reflects the significant ongoing advancements in the wide range of gaseous detector technologies and applications, as well as the growing needs for future detectors

Large area Muon Systems and Inner Trackers

- **MPGD:**
    - P. Iengo "Pixelized Micromegas for Future Detectors"
    - E. Sidoretti "The hybrid u-RWELL: a new high performance resistive MPGD"
    - M. Alexeev "New large area Micromegas detector and readout ASIC for the AMBER experiment at CERN"
        - Also **addressing challenges on front-end electronics**

- **RPC – addressing challenges on ECOGAS:**
    - L. Quaglia "Eco-friendly RPCs for future HEP applications: an insight into signal shape and rate studies"

Astroparticle physics

- **MPGD**
    - S. Tugliani "Characterization of IXPE Gas Pixel Detectors with the X-ray Calibration Facility "
- **GEM based detector -- addressing innovative production technique**
    - A. Lega "R&D on Plasma-Etched Gas Electron Multipliers for X-ray Polarimetry in Space"
- **TPC**
    - D. Fiorina "A Large-Volume, Extended Field-of-View TPC for X-Ray Polarimetry"
    - S. Piacentini "Towards a large gaseous TPC with optical readout: the CYGNO project "
    - S. Scarpellini "Development of a compact readout of time projection chambers for future $\mu \rightarrow e \gamma$ experiments"

Discussion at the end of the session