Muon Detection at Colliders: Part 2

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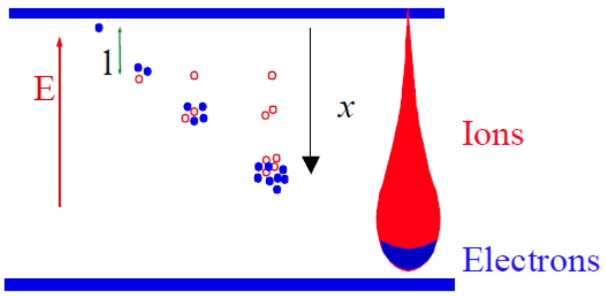
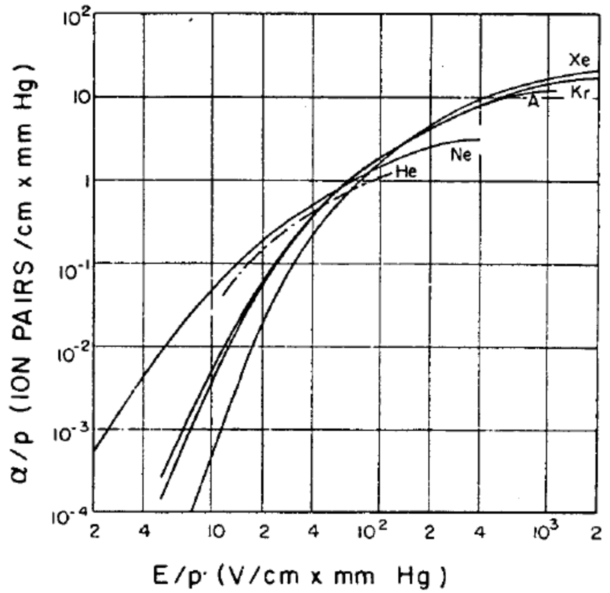
Complications and Future Directions

- Some Complications
  - Space Charge
  - Aging
  - Green house-gas mixtures
- Future directions
  - Micropatterns to improve spatial resolution
  - Timing improvements for future colliders

Recall Basic Principle: Ionization, Amplification, Readout

CHARGE MULTIPLICATION IN UNIFORM FIELD





S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)

Mean free path for ionization:

$$\lambda = \frac{1}{N\sigma} \qquad N\text{: molecules/cm}^3$$

Townsend coefficient:

$$\alpha = \frac{1}{\lambda} \qquad \text{Ionizing collisions/cm} \qquad \frac{\alpha}{P} = f\left(\frac{E}{P}\right)$$

Incremental increase of the number of electrons in the avalanche:

$$dn = n\,\alpha\,dx$$

Multiplication factor (Gain): $M(x) = \frac{n}{n_0} = e^{\alpha x}$

Maximum Avalanche size before discharge (Raether limit):

$$Q_{MAX} \approx 10^7 \text{ e}$$

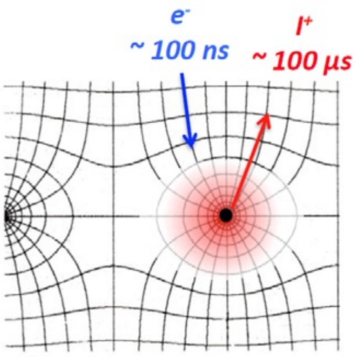
H. Raether, Electron Avalanches and Breakdown in Gases (Butterworth 1964)

Space Charge

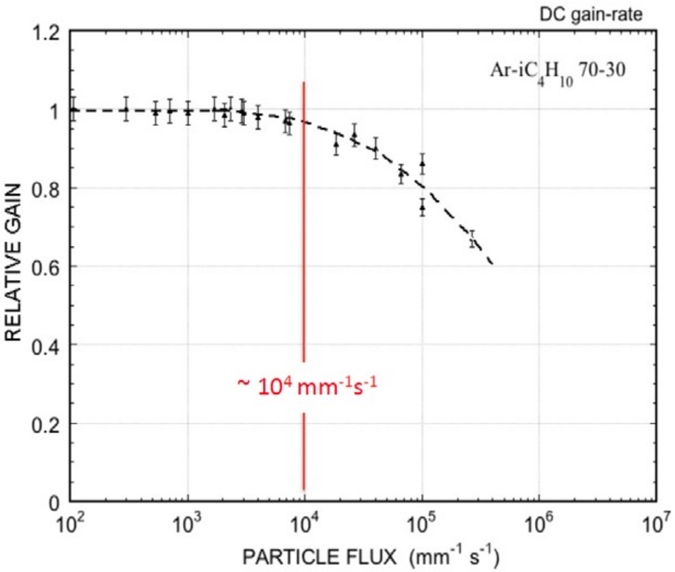
RATE-DEPENDENT GAIN REDUCTION

SPACE CHARGE

SPACE CHARGE NEAR THE ANODE:
BUILDUP OF SLOW POSITIVE IONS
MODIFIES THE ELECTRIC FIELD

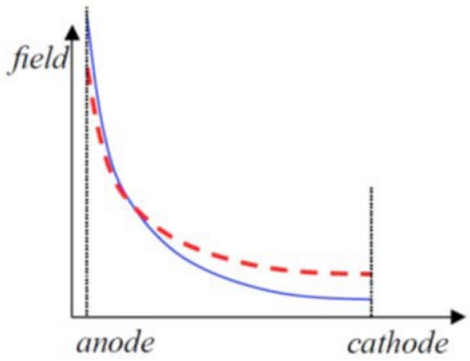


RELATIVE GAIN AS A FUNCTION OF RATE:



A. Breskin et al, Nucl. Instr. and Meth. 124(1974)189

- With higher particle flux the build up of slow positive ions can get large enough that it significantly shields and modifies the electric field lowering the effective gain

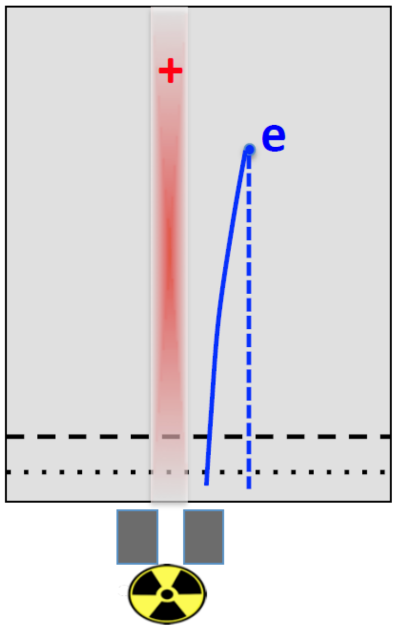


Space Charge: Resolution Effects

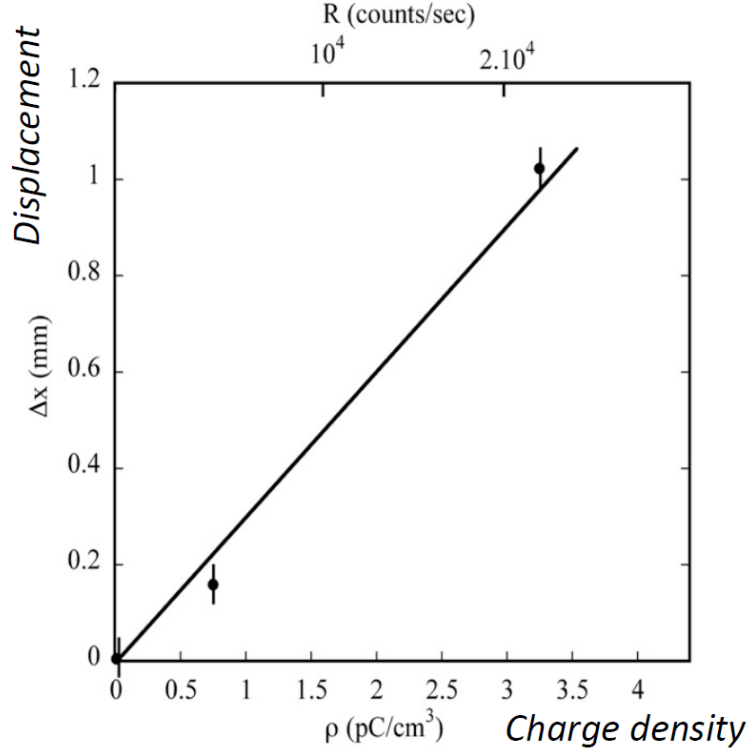
POSITIVE ION BACKFLOW

SPACE CHARGE

LATERAL DISPLACEMENT OF ELECTRONS DRIFTING NEAR A POSITIVE IONS COLUMN



^{55}Fe SOURCE 1 cm FROM ION COLUMN
10 cm DRIFT

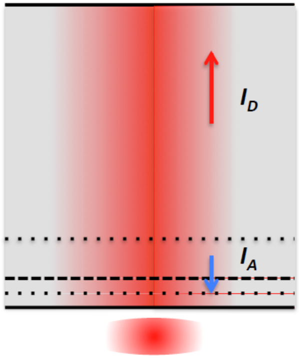


D. Friedrich, et al, Nucl. Instr. and Meth. 158(1979) 81

Space Charge: Track Distortion

POSITIVE ION BACKFLOW

SLOW POSITIVE IONS ACCUMULATE IN THE DRIFT VOLUME AND MODIFY THE FIELD RESULTING IN TRACKS DISTORTIONS:



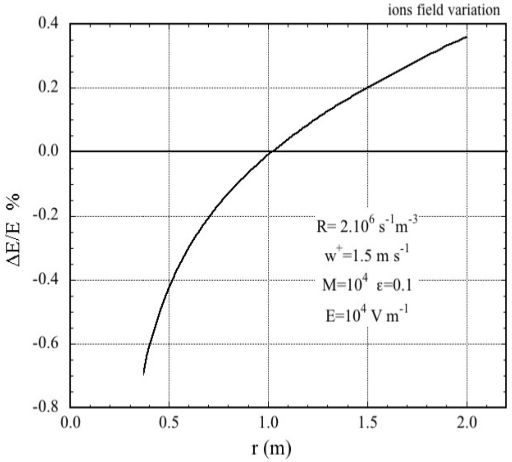
IONS BACKFLOW RATIO $IBF = \frac{I_{DRIFT}}{I_{ANODE}}$

THE WISH: $IBF \le \frac{1}{GAIN} \approx 10^{-4}$

MWPC: IBF ~ 30%

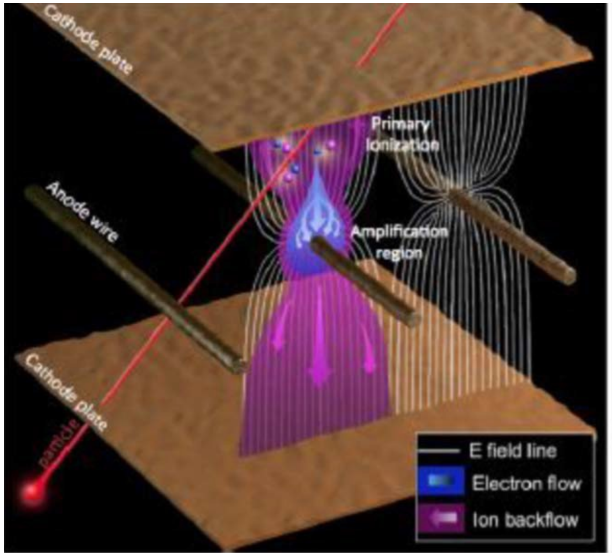
RELATIVE DRIFT FIELD MODIFICATION (ALEPH MWPC-TPC)

SPACE CHARGE



GATING:
ADD A WIRE MESH WITH VOLTAGE-CONTROLLED TRANSPARENCY

POSSIBLE AT LOW RATES:
Maximum electron drift time
< Time between events

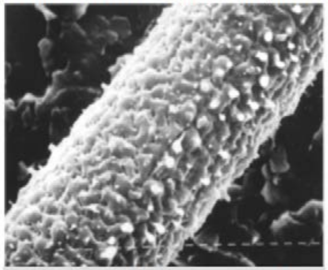


Aging

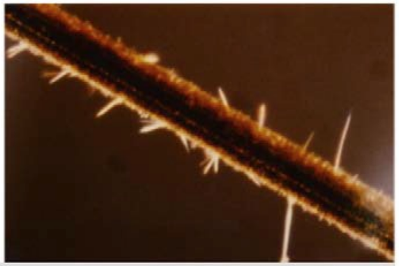
AGING

SECONDARY PROCESSES

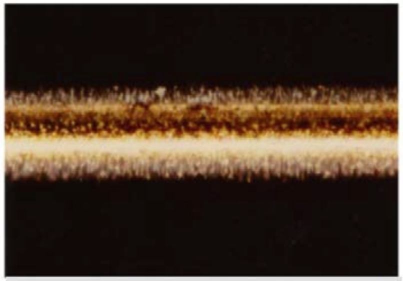
Polymerization of organic compounds with formation of deposits on thin wires:



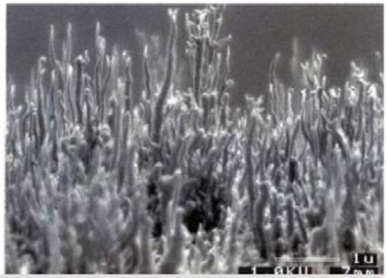
O. Ullaland, LBL-21170 (1986)107



I. Juric and J. Kadyk, LBL-21170 (1986)141



I. Juric and J. Kadyk, LBL-21170 (1986)141



M. Binkley et al,
Nucl. Instr. and Meth. A515(2003)53

- In the plasma that is created there can be complicated chemical reactions between gas and various pollutants.
- Result is highly reactive hydrocarbons with high electronegativity created
- This leads to insulating deposits on cathode and anode
- Field distortion, gain reduction, track distortion, resolution worsens

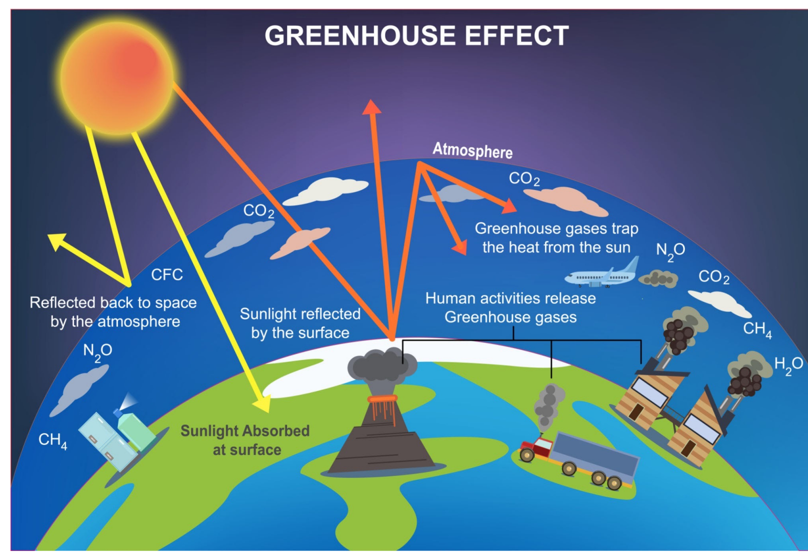
GREENHOUSE GASES

Scientists at CERN hunt for greener gases for particle detectors

The Large Hadron Collider discovered the Higgs boson. Now the facility's researchers are searching for more environmentally friendly gases to run its detectors

by ***Sam Lemonick***

April 27, 2019 | A version of this story appeared in **Volume 97, Issue 17**



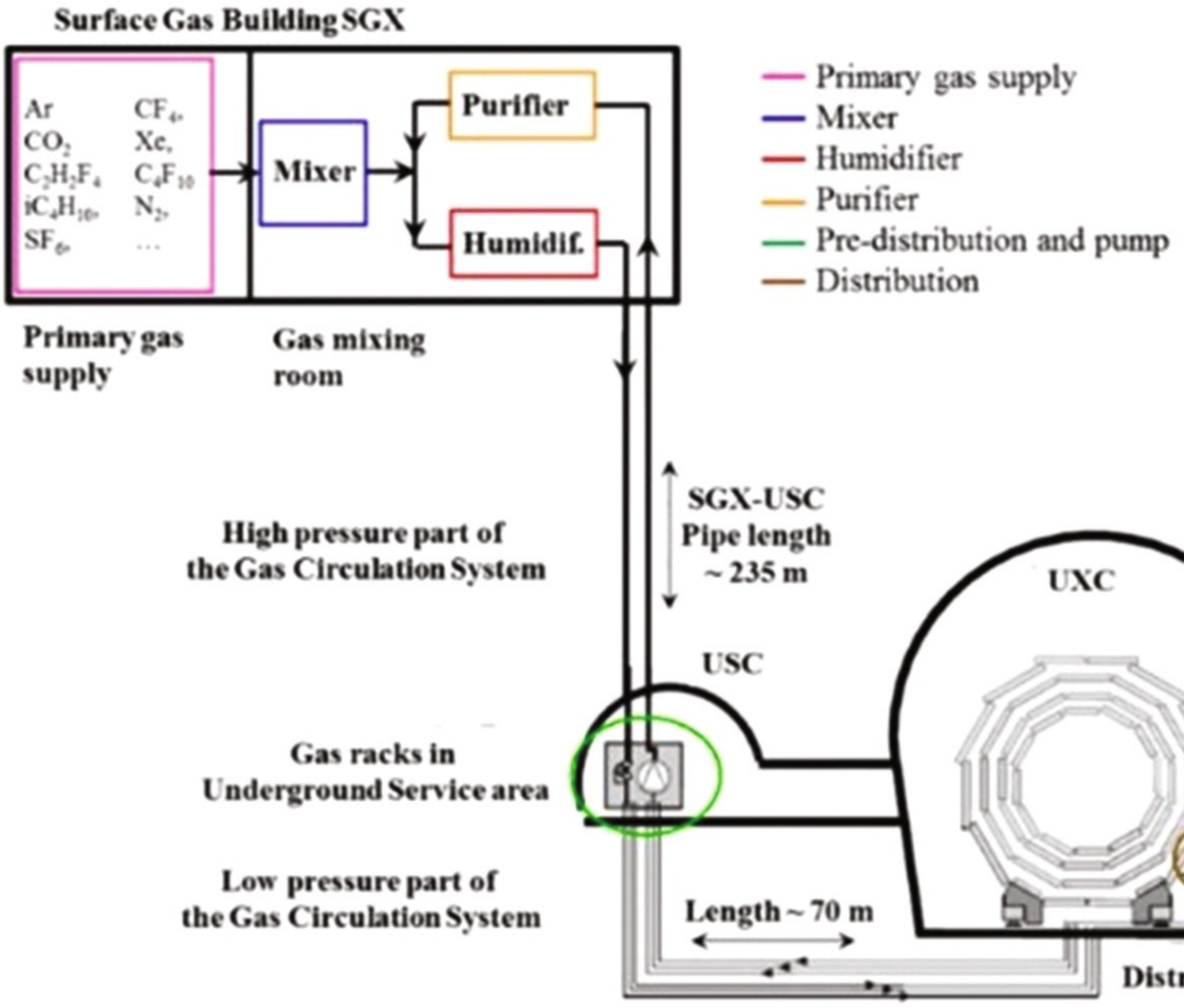
What makes a gas a greenhouse gas?

- Recall that the greenhouse effect is caused when radiation from the sun (peaking in the optical and UV range) heats up the earth
- Part of that energy absorbed is radiated by the earth as it cools down
- However, earth radiates significantly in the IR region
- Greenhouse gases in the earth's atmosphere are those that are relatively transparent to optical frequencies but highly absorptive in IR region
- The presence of these gases tends to lead a warming of the earth as they effectively let heat in but keep it from leaving

Quencher Gas

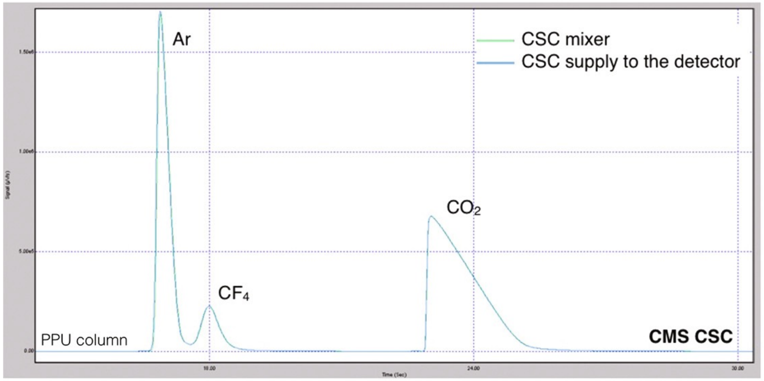
- Recall from yesterday that besides the main ‘absorber’ gas we also need a ‘quenching’ gas
- The purpose of the quencher is to absorb photons produced in the avalanche and stop the process of a “continuous” avalanche from forming which makes the detector useless as a detector
- The main properties of the quencher are the ability to absorb photons with less energy than typical simple atoms. Typically diatomic or polyatomic molecules with many rotational and vibration lower energy modes available
- This is exactly the property that makes a greenhouse gas!

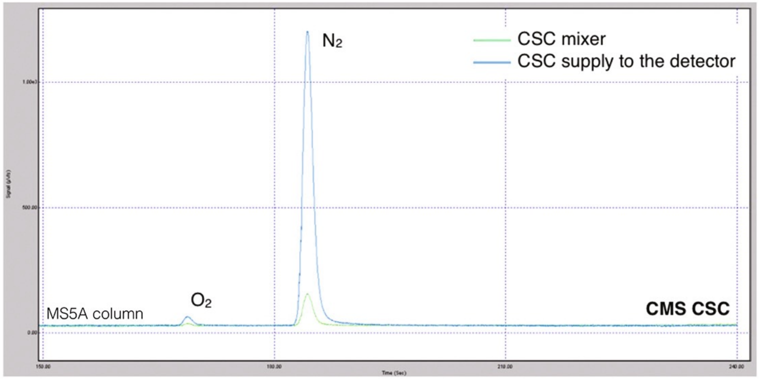
Gas Systems


Surface Gas Building SGX
Ar
CO₂
C₂H₂F₄
iC₄H₁₀,
SF₆,
CF₄,
Xe,
C₄F₁₀
N₂,
...
Mixer
Purifier
Humidif.
Primary gas supply
Gas mixing room
Primary gas supply
Mixer
Humidifier
Purifier
Pre-distribution and pump
Distribution
High pressure part of the Gas Circulation System
SGX-USC Pipe length ~ 235 m
UXC
USC
Gas racks in Underground Service area
Low pressure part of the Gas Circulation System
Length ~ 70 m
Distribution racks

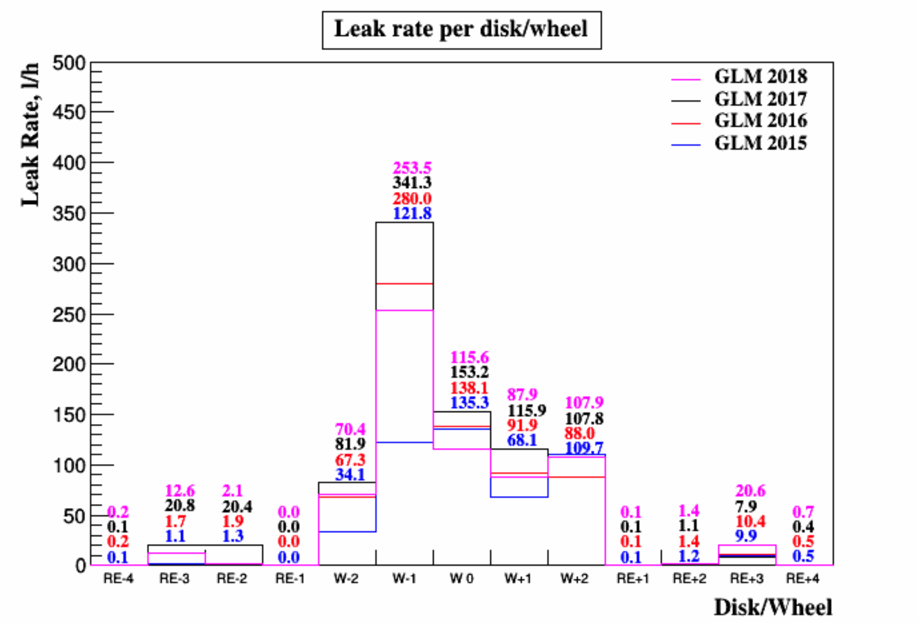
Gas Monitoring

- Mix and monitor the composition of the gas
- Typical results shown below





Leaks!



Total leak rate: 673 l/h (2018), (11 channels were disconnected during TS2/2017)
860 l/h (2017),
682 l/h (2016).

Nearly ~1000 liters of gas per hour leaked
Into the atmosphere!

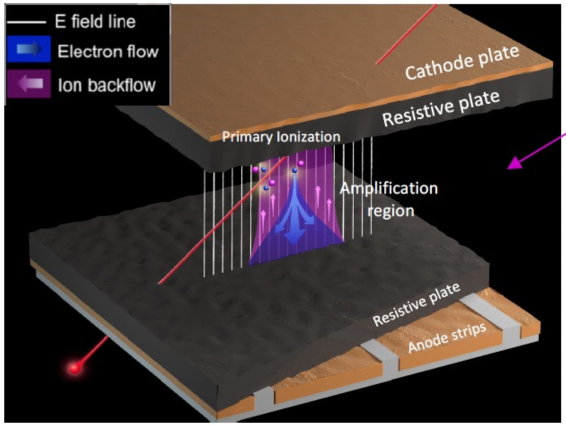
Future Directions

- Moving forward we would like to continue or quest for
  - Radiation Hard detectors that can withstand high radiation environments
  - Improved spatial resolution to improve on measurement on momentum of particles in the spectrometer
  - Improved timing resolution to help identify hits from primary particles of interest from background particles

Future Technology … according To AI

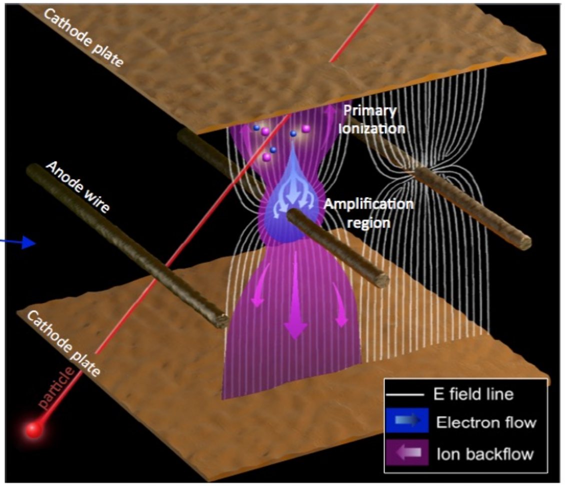
Evolution to smaller microstructures

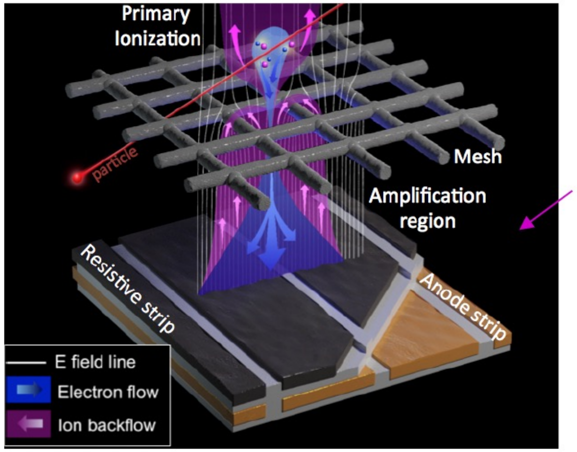
Examples of Amplification Structures



Resistive Plate Chamber (**RPC**): amplification in the gas gap

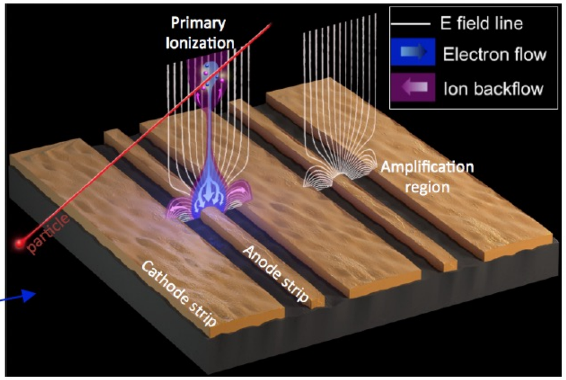
Multi-Wire Proportional Counter (**MWPC**): amplification in the vicinity of the anode wires



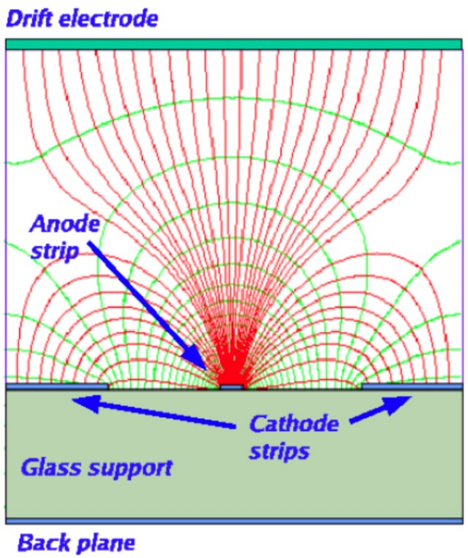


MicroMesh Gaseous Detector (**MicroMegas**): Amplification between a microscopic mesh and the anode plane

Micro-Strip Gas Chambers (**MSGC**): amplification in the vicinity of the anode micro-strips



First Micropattern Gas Detectors (MPGD)



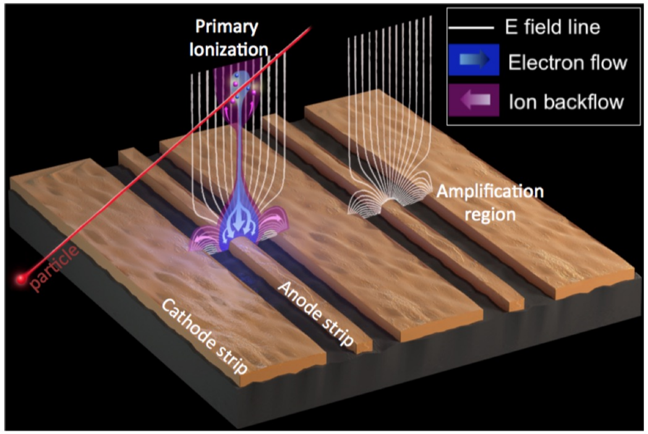
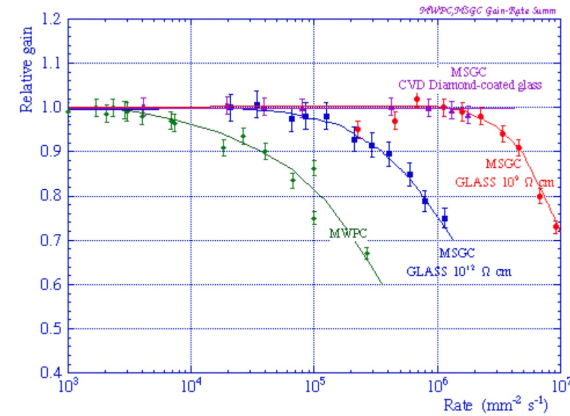


FIGURE 4.22: Schematic representation of a MSGC in operation.

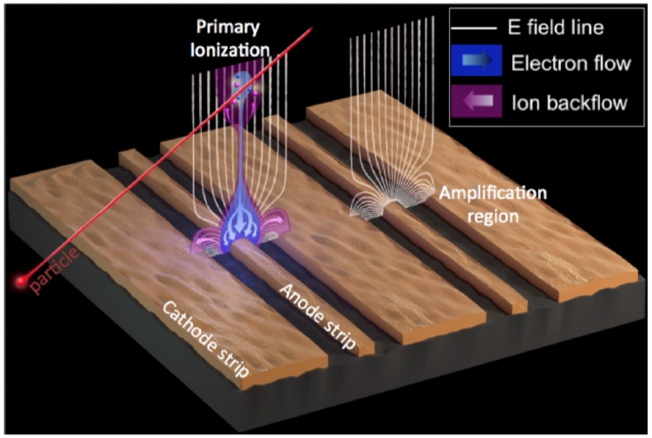


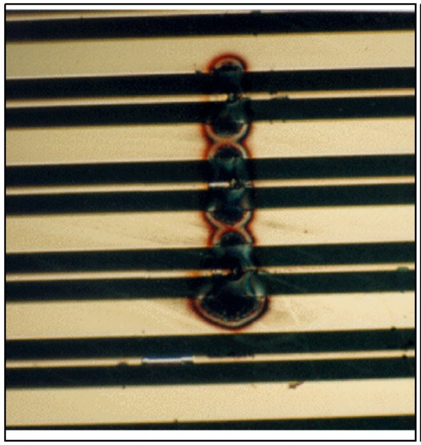
- First developed in 1988, smaller structure , more intense electric fields
- Reduction of space charge effects leads to higher rate capability with constant gain

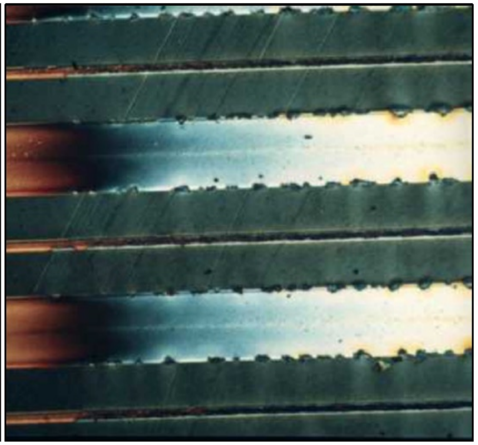
Discharges

Some limitations:

- ❖ Good performance in high-rate environment, but the operation is limited by the discharge probability
  - ➢ Small distance between electrode boosts the possibility for a large avalanche to develop into a stream between anode and cathode = discharge
  - ➢ The energy released during a discharge can permanently damage the electrodes

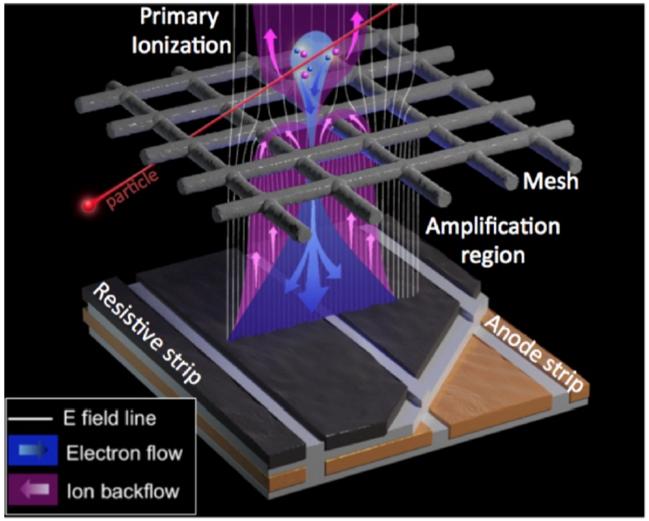




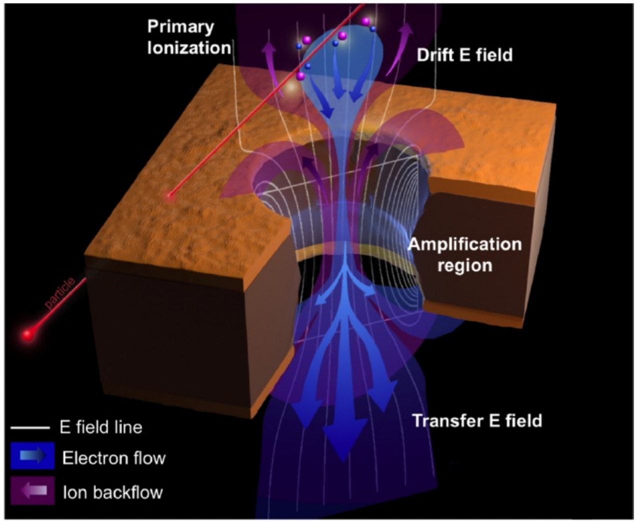


New Solutions:

- Modern MPGD introduced with the MICRO-MEsh GASeous (Micromegas - 1992) and the Gas Electron Multiplier (GEM - 1996) technologies
  - Specifically developed for high-rate applications with improved longevity and reliability
  - Start of the golden age of MPGDs
  - Many variants and daughter technologies based on Micromegas and GEM concepts



Micromegas

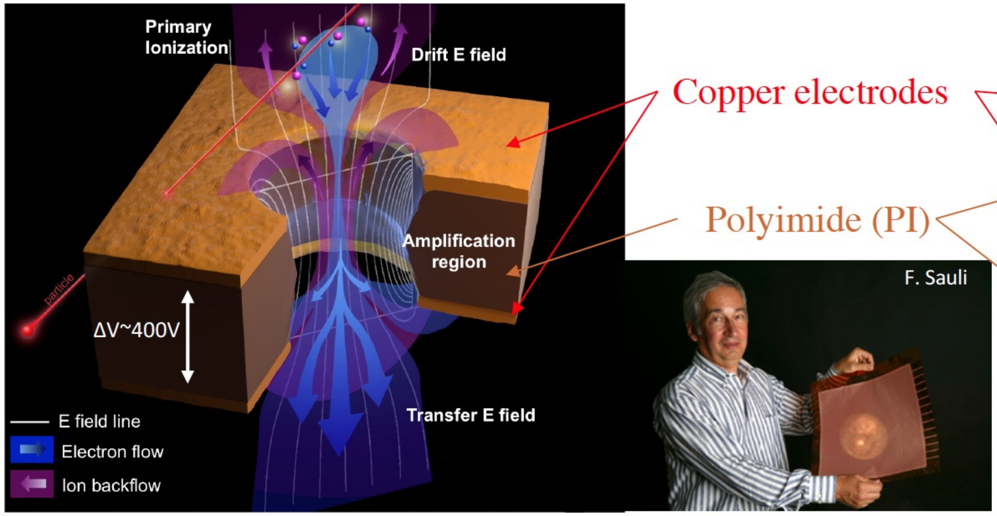


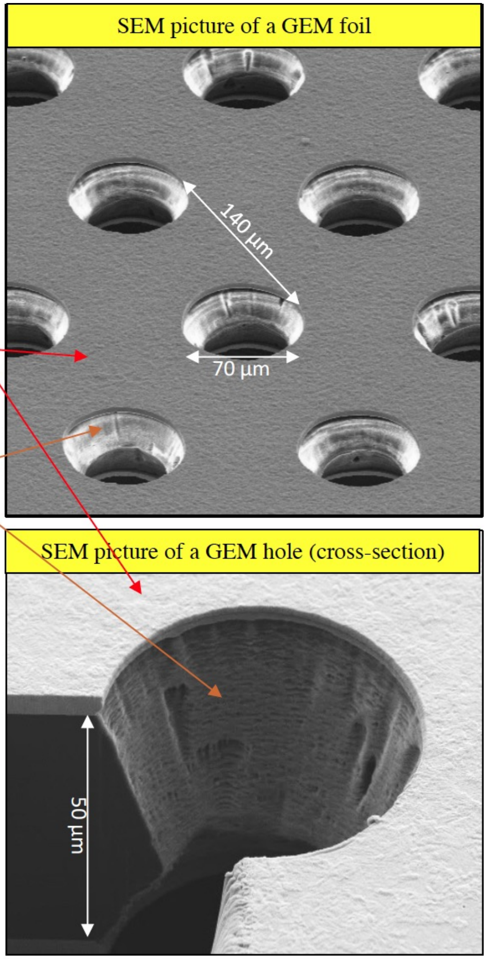
GEM

GEMs

Basic Principle

The concept of **G**as **E**lectron **M**ultipliers (**GEM**) was introduced by Fabio Sauli in 1996-97 in order to pre-amplify signals in MSGCs – GEM are one of the main **MPGD** in use in HEP experiments





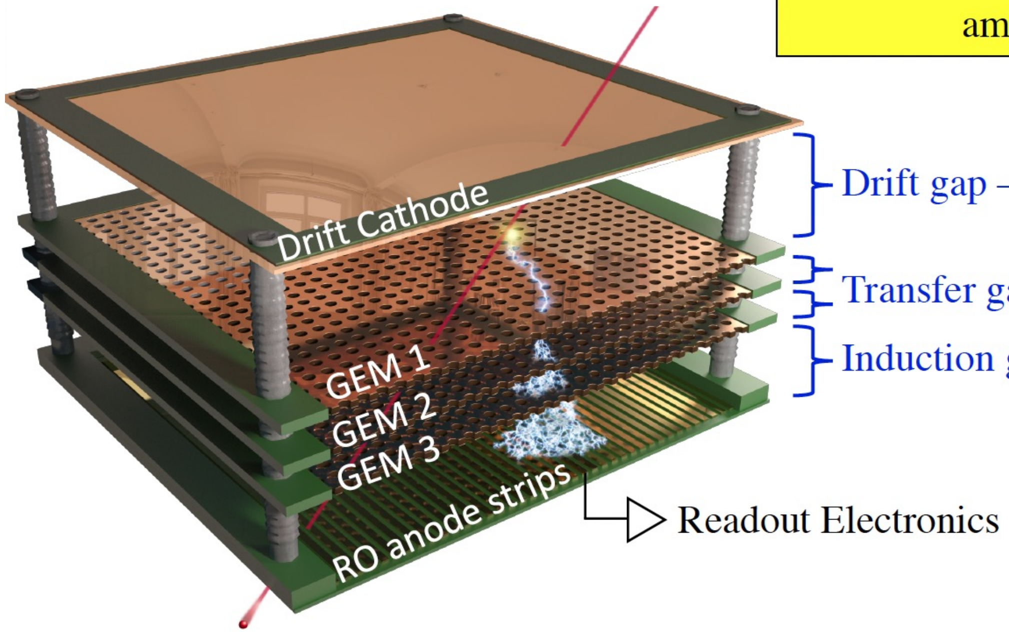
Electrons entering the GEM holes will accelerate in the intense electric field (~80 kV/cm) and provoke the ionization of gas molecules, giving rise to an electron avalanche

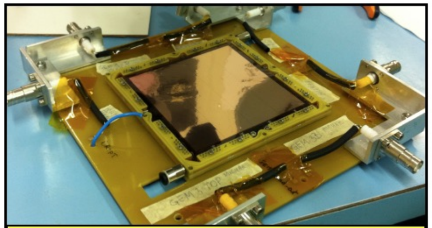
Multiplication: 1 e^- input → 20 e^- output (max 10^3 e^-)

Tripple GEM

Basic Principle

A GEM foil is NOT a detector, it's just an amplification structure





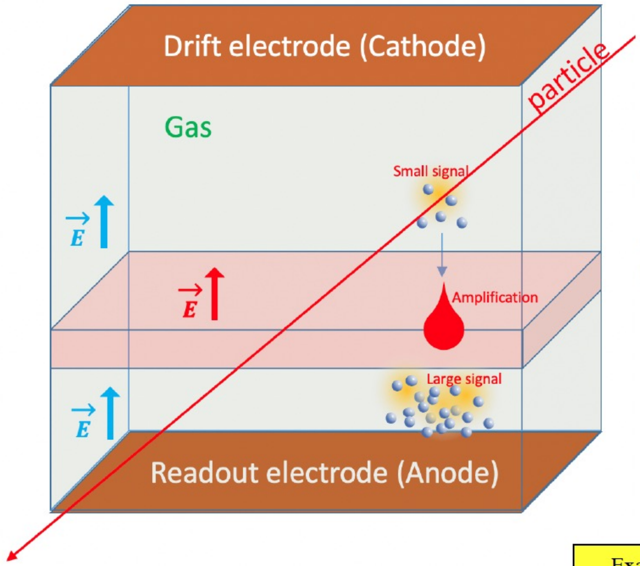
A 10x10 cm² triple-GEM detector

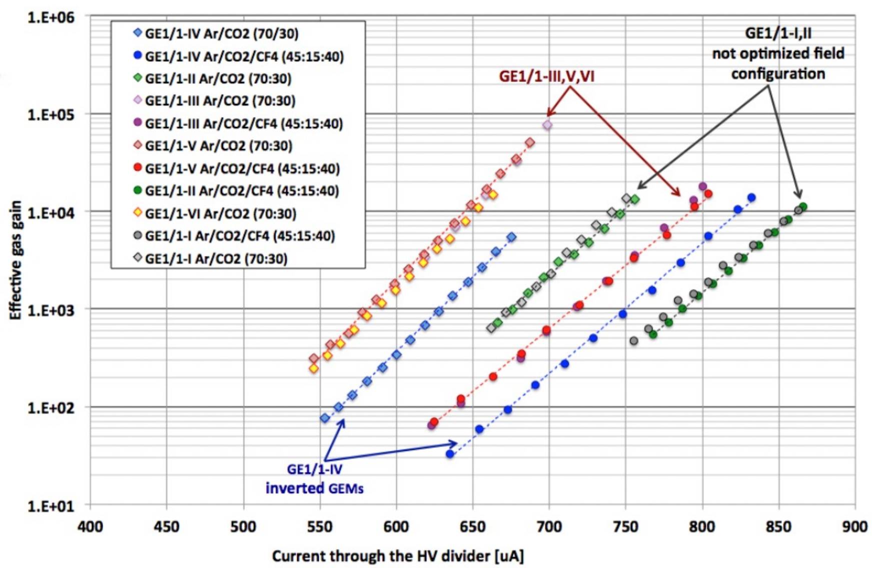
- GEM foils can be used in a gas volume with a Cathode (Drift) and Anode strips (Readout) to form a full particle detector
- Using several GEMs in series, we can multiply electrons with gains up to $10^4 - 10^5$

→ This is the famous **Triple-GEM** detector

The effective gas gain: a central parameter

$$Gain = \frac{I_{out}}{Rate \times Nb_{primaries} \times q_e}$$

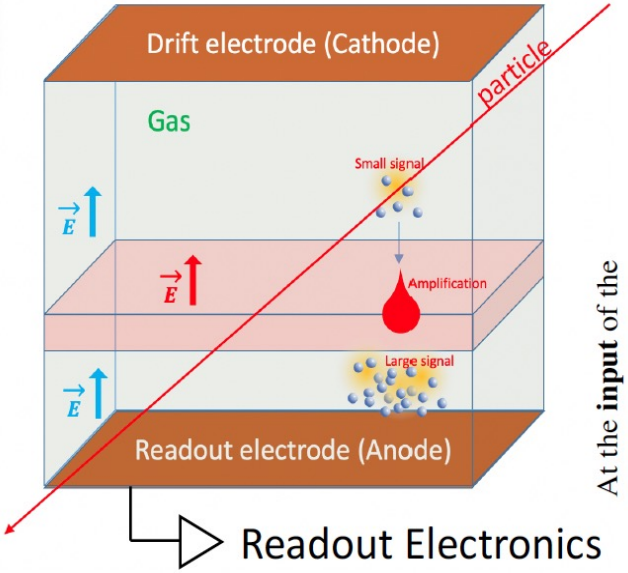




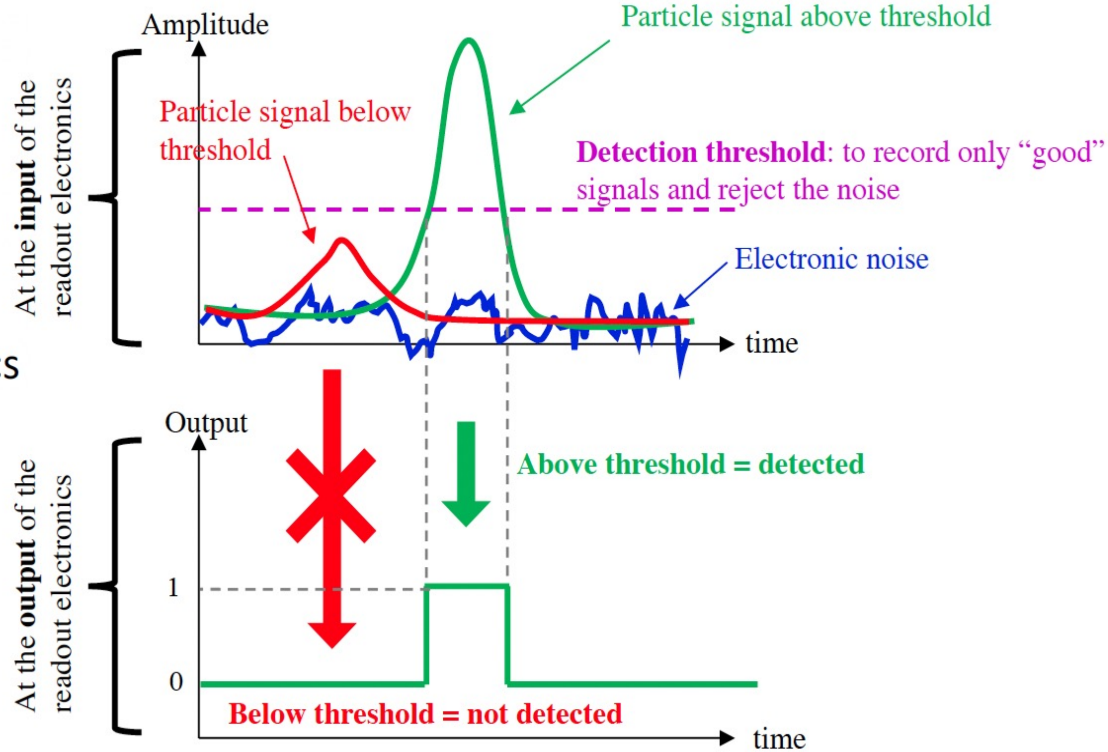
Example of gain curves as a function of the HV supply for the different GE1/1 prototype generations

Definition

The detection efficiency is the probability to detect a signal when a particle is crossing the detector
→ Property of detector + electronics

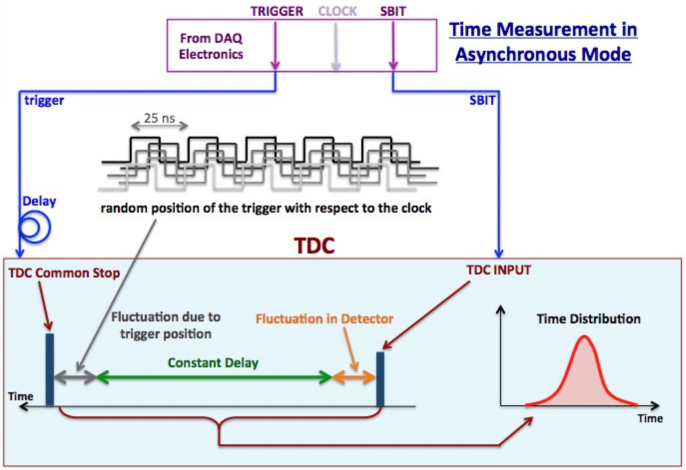


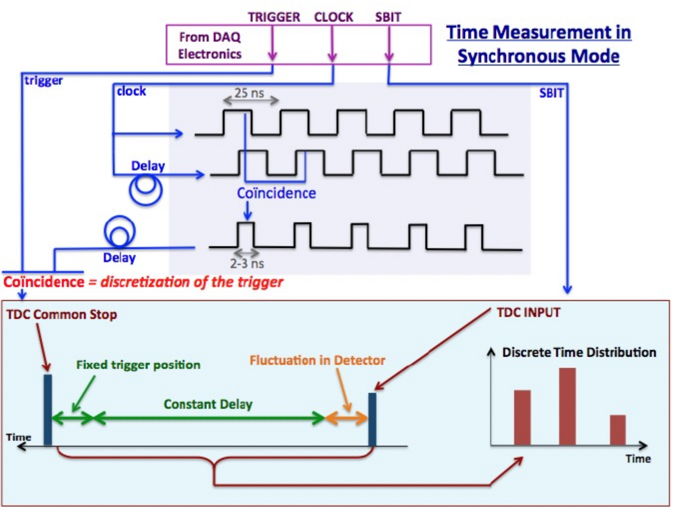
How does it work?



The binary electronics only output signals when the input charge is overcoming a defined threshold
All signals below the threshold are **not detected**

How to measure the timing resolution





- Measuring the time resolution is **complex** … it requires a full understanding of all elements in the system and a sufficient **precision** to identify fluctuations of the order of the **nano second**
- In practice, we compare the **time of arrival** of a **reference signal** coming from a set of scintillators and the **output signal** of the detector under test
- Both signals are sent to a Time to Digital Converter (TDC) which measures precisely the time difference:
  - **Asynchronous mode**: the time resolution is extracted from the time difference distribution directly from the TDC
  - **Synchronous mode**: the reference signal is synchronize with a 25ns clock to represent the actual bunch crossing scheme in CMS

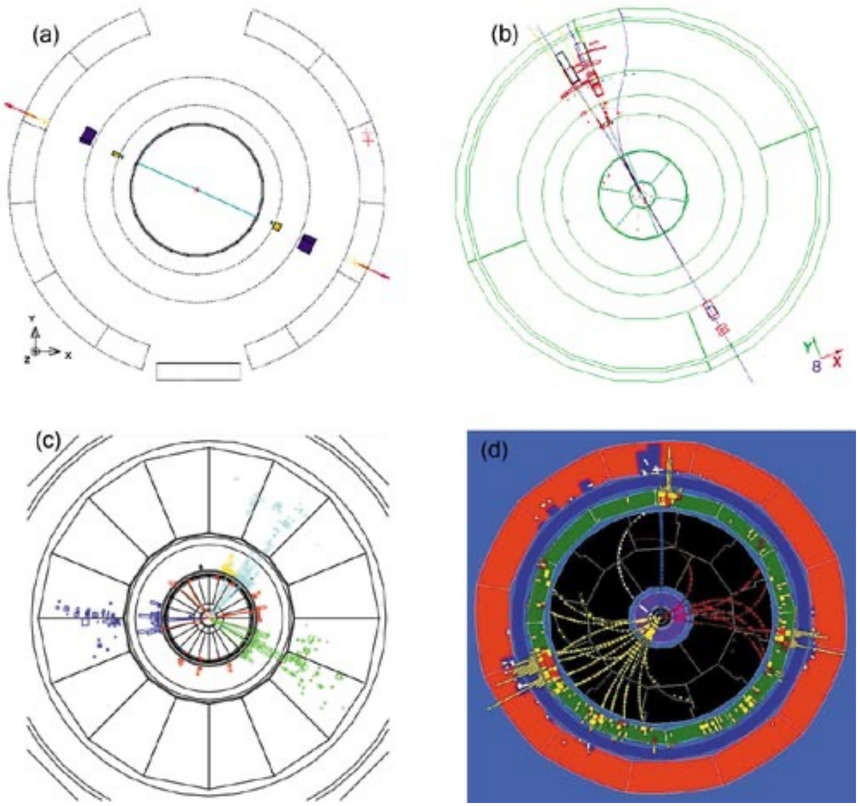
Future Colliders and Muon Detection

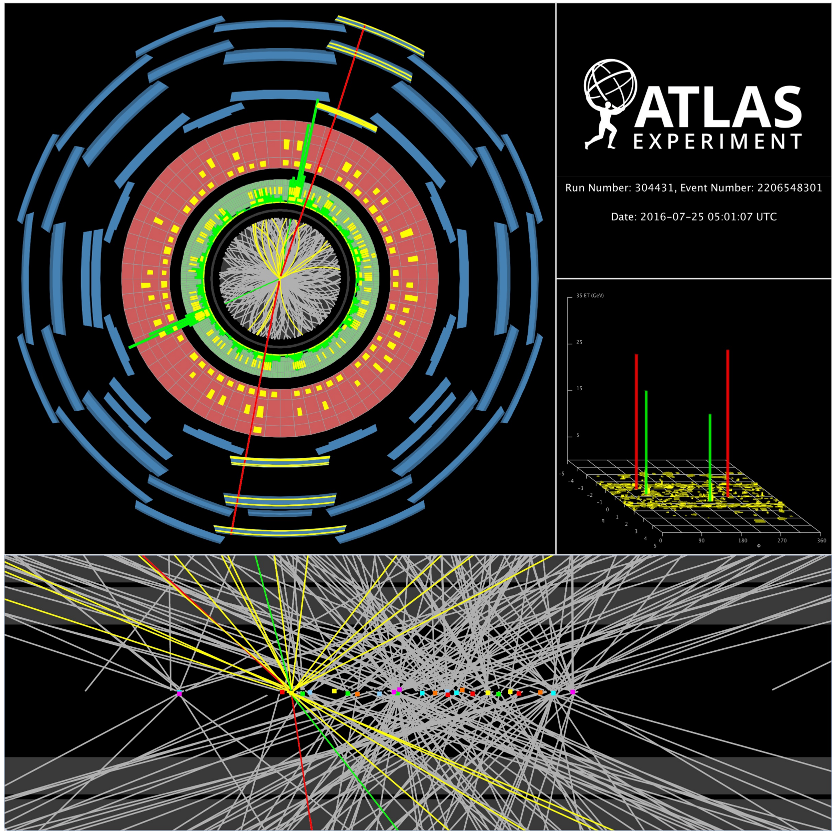
- Many possible machines being discussed
  - FCC-ee/CPEC/ILC – Large either circular or linear electron machine with the goals of producing a large number of Higgs, Z, W events with very little background and complete kinematic constraints (**conventional technology for muons available today should be good for physics goals – concentrate on best resolution possible**)
  - FCC-hh – 100 TeV pp machine after FCC-ee (**high pileup, high radiation environment)**
  - MuCol 1-10 TeV **(central region very similar to ee, forward region very high beam induced background)**

Future electron/positron

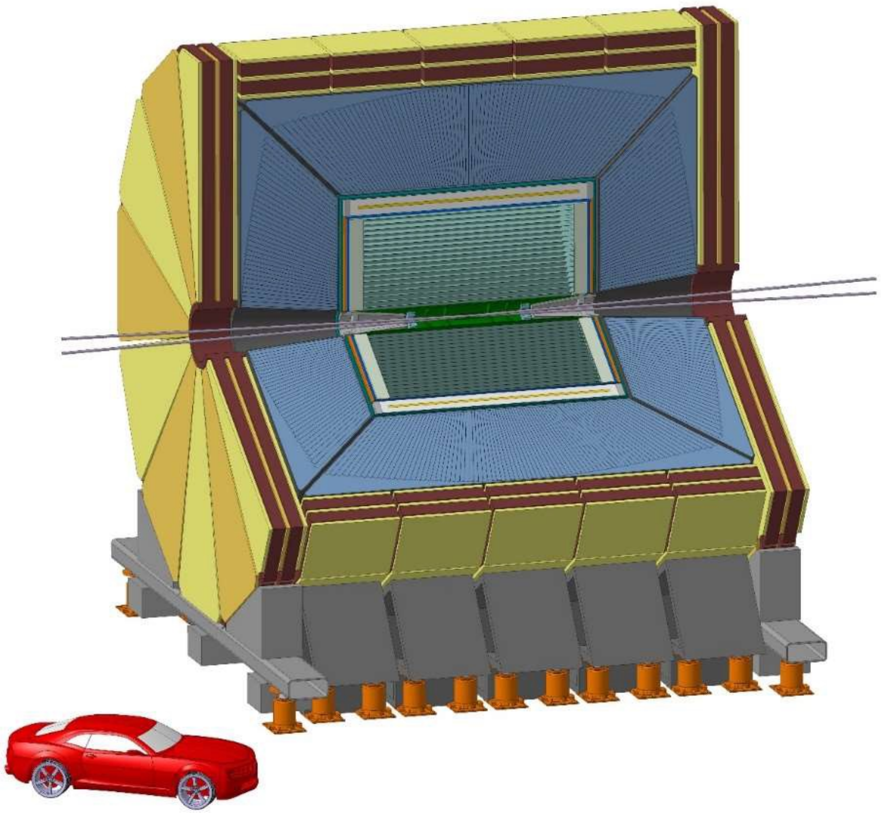
- Electrons are fundamental particles so essentially every collision is a fundamental interaction between two point particles
- In particular, in comparison to the the LHC there is no "underlying" event
- Accelerator run such that ~1 fundamental interaction per crossing, very little background except for some minor Bhabba Scattering
- Completely kinematically constrained – in proton proton collisions it is quarks and gluons that are colliding which we don't know the z component of the momentum.
- In e+e- collisions total momentum of initial state is 0 for the collision of interest

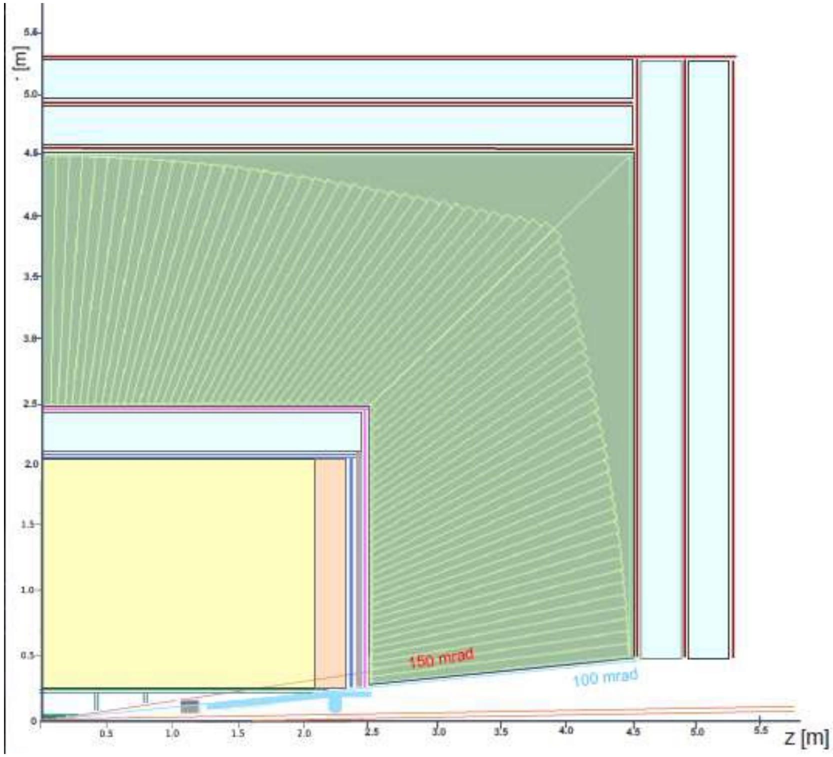
Electron – Positron Events (LEP) versus LHC events





Example Possible FCC-ee detector





Micro-Rwell detectors

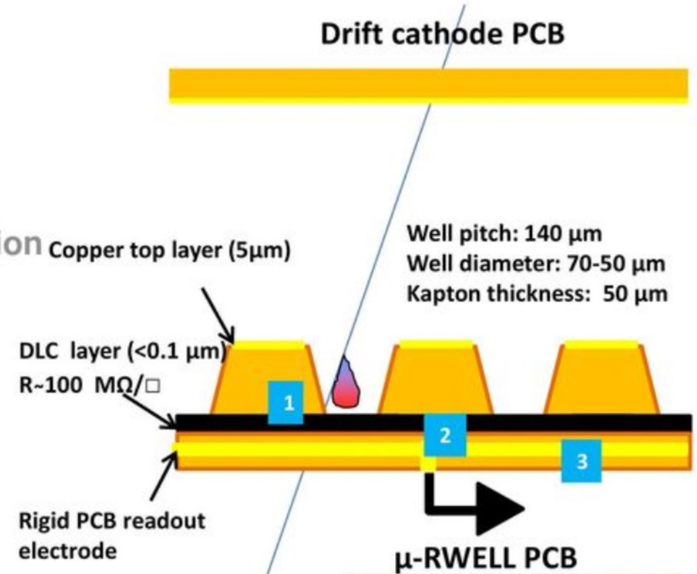
The detector architecture

The **μ-RWELL is composed of** only **two elements**: the **μ-RWELL_PCB** and the **cathode**

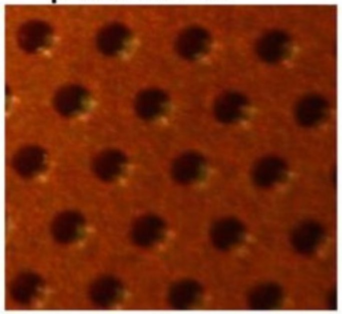
The **μ-RWELL_PCB, the core of the detector,** is realized by **coupling:**

- a "**suitable patterned kapton foil**" as "**amplification stage**"
- a **"resistive layer"** for discharge suppression & current evacuation:
  - **"Single resistive layer" (LR) <<100 kHz/cm^2:** single resistive layer □ surface resistivity ~100 M□/□ (CMS-phase2 upgrade; SHIP)
  - **"Double resistive layer" (HR) > 1 MHz/cm^2**: more sophisticated resistive scheme is implemented (MPDG_NEXT- LNF) suitable for LHCb-Muon upgrade
- a **standard readout PCB**

G. Bencivenni et al., 2015_JINST_10_P02008



μ-RWELL PCB

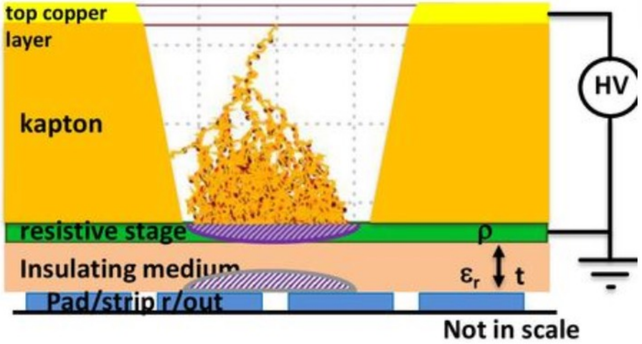


(*) DLC = Diamond Like Carbon
High mechanical & chemical resistant material

How they work

Principle of operation

Applying a suitable voltage between top copper layer and DLC the "**WELL" acts as multiplication channel for the ionization.**

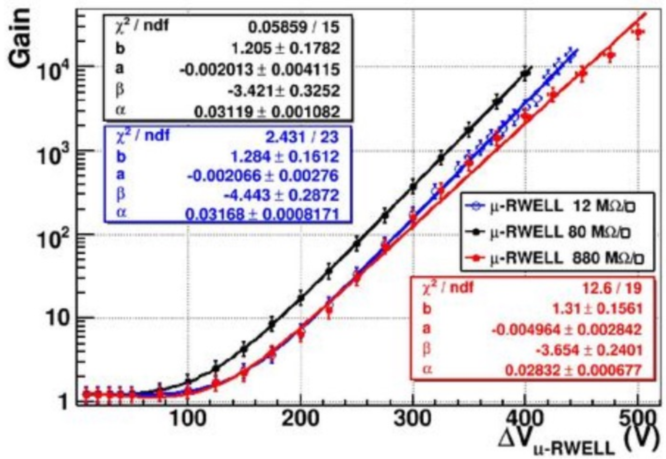


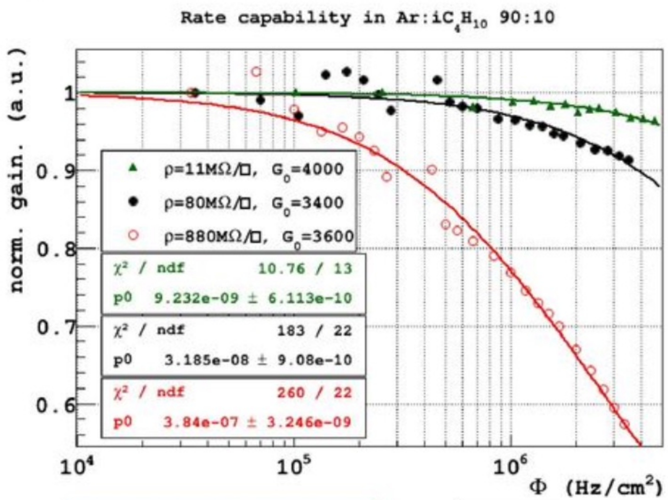
The charge induced on the resistive foil is dispersed with a ***time constant, $\tau = \rho C$,*** determined by

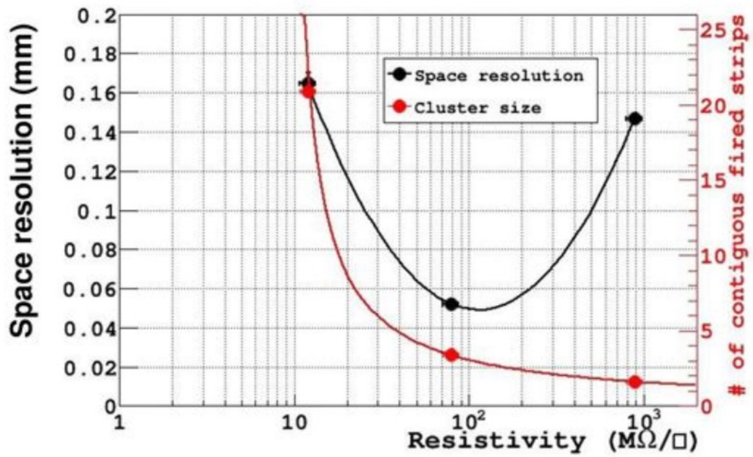
- the ***surface resistivity, ρ***
- the ***capacitance per unit area,*** which depends on the **distance between the resistive foil and the pad readout plane*, t***
- the ***dielectric constant*** of the insulating medium, ε_r *[M.S. Dixit et al., NIMA 566 (2006) 281]*

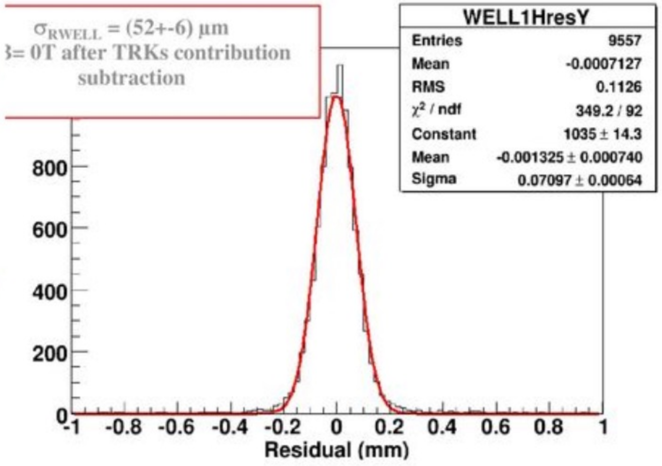
- **The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark**
- As a drawback, the **capability to stand high particle fluxes is reduced**, ***but an appropriate grounding of the resistive layer with a suitable pitch solves this problem (see High Rate scheme)***

Single-layer performance









Already prototypes

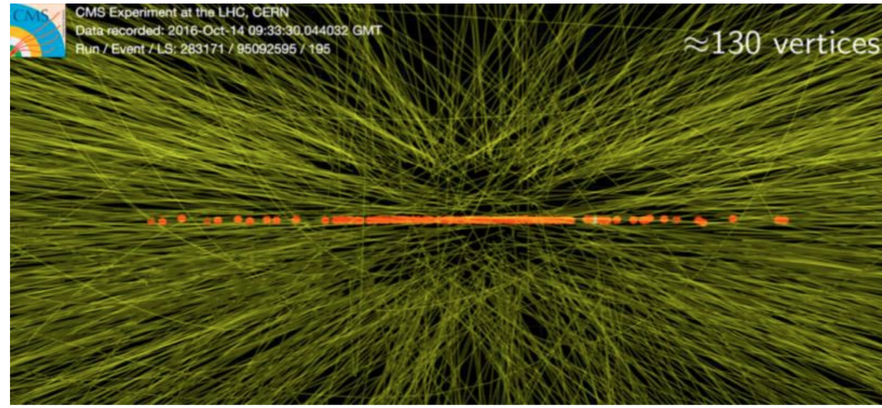
Muon chambers R&D

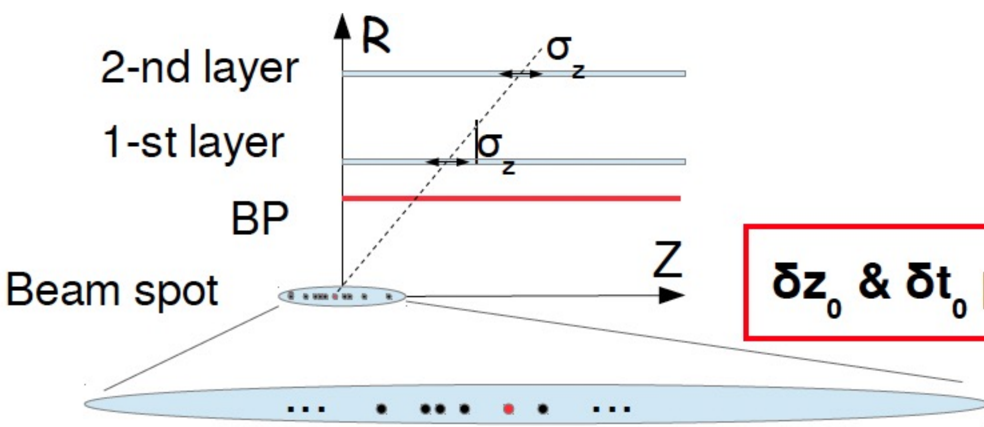
- μRwell:
  - Concept proved/Synergy with LHC
    - Focus on Single resistive layer for high rate
    - G. Bencivenni et al., 2019_JINST_14_P05014
  - R&D for large area 50x50 cm^2
    - Industrialization
    - Cost reduction
    - DLC+Cu sputtering
    - 2D readout

CMS GE2/1 with 2 μRwell 2 m x 1.2 m

FCC-hh environment

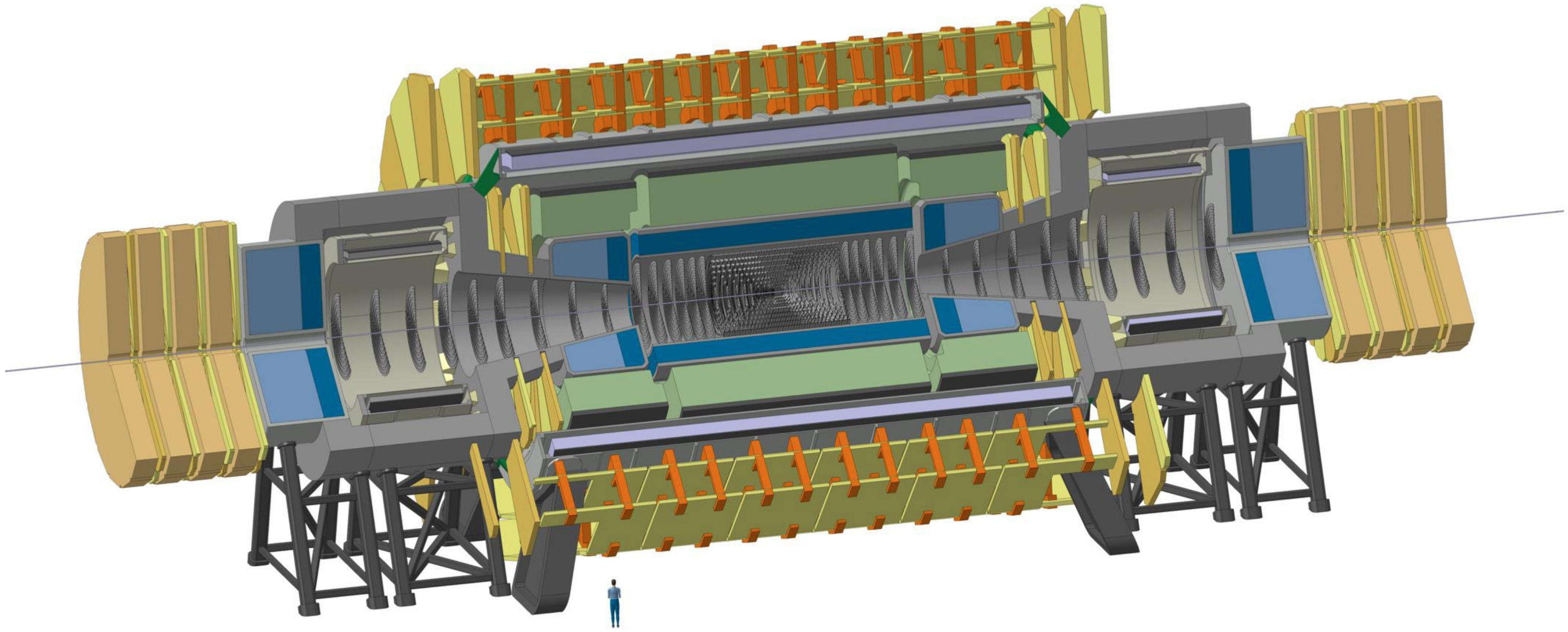
- The HL-LHC is expecting something on the order of an average of 140 pp vertices per event
- FCC-hh is envisioned to run an environment an **order of magnitude more** pileup events ~1000 pp verticies per event



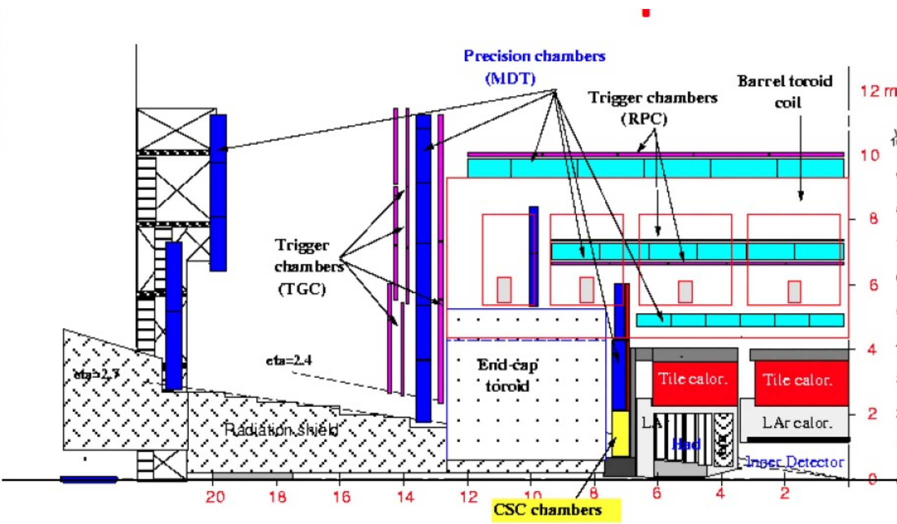


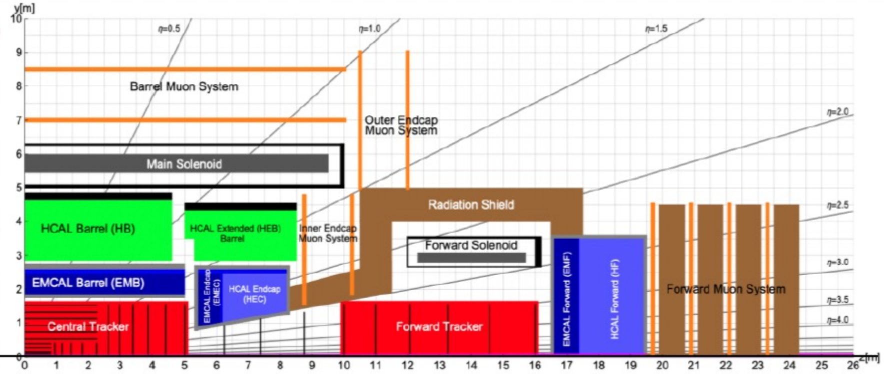
δz_0 & δt_0 play the crucial role!

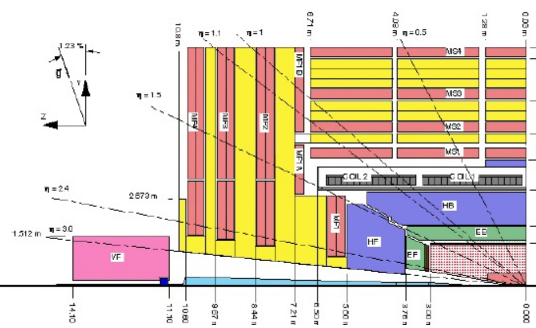
FCC-hh Reference detector

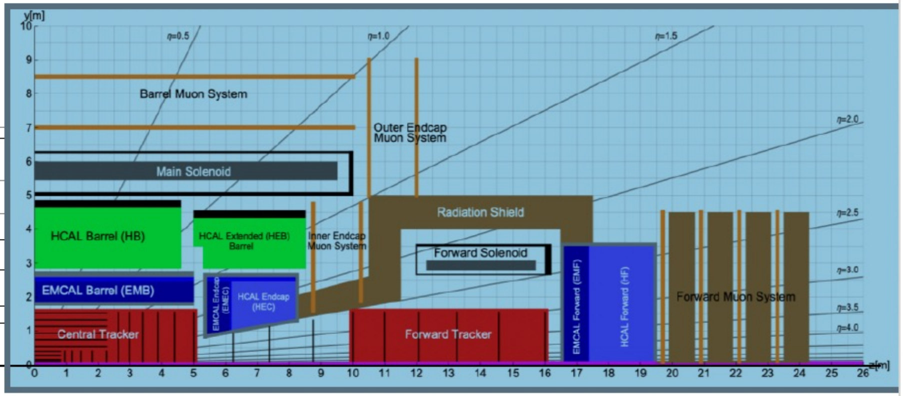


Comparison to CMS and ATLAS

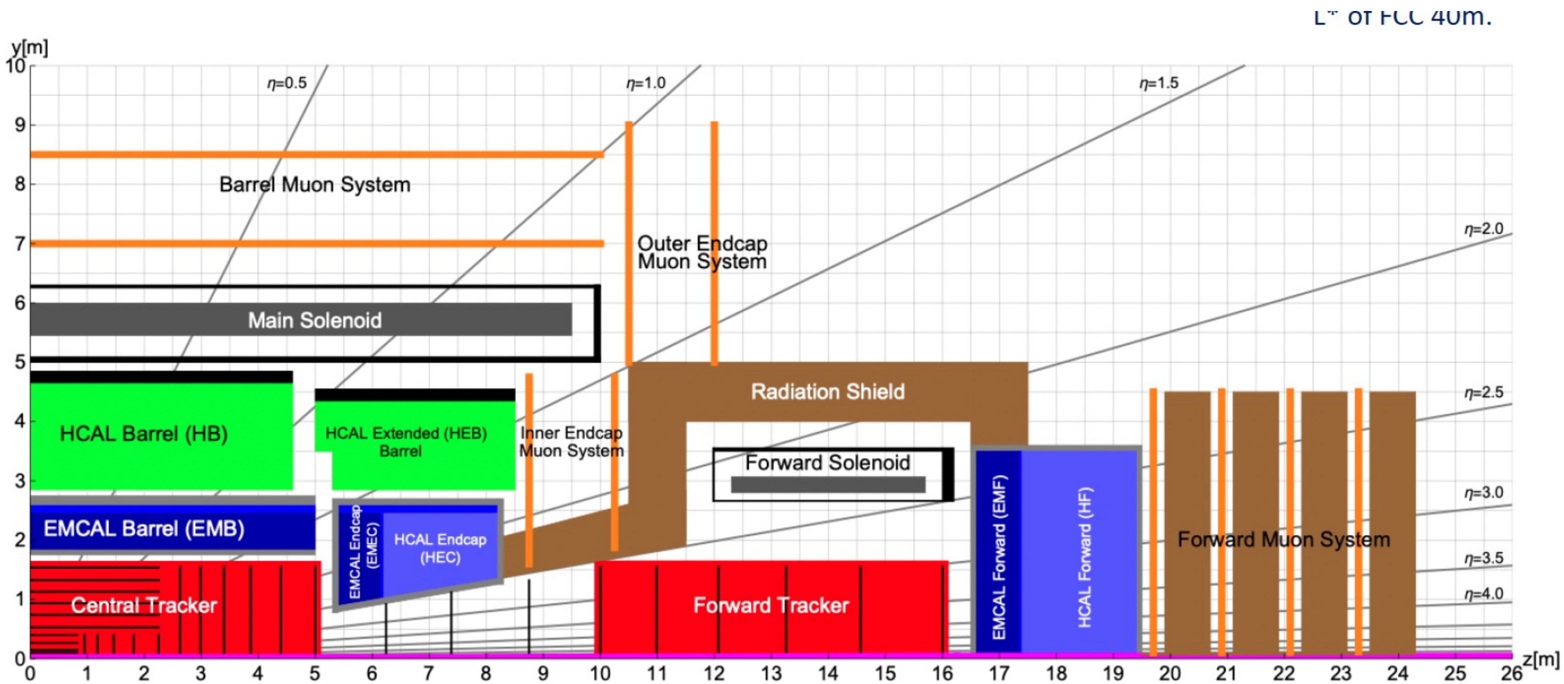








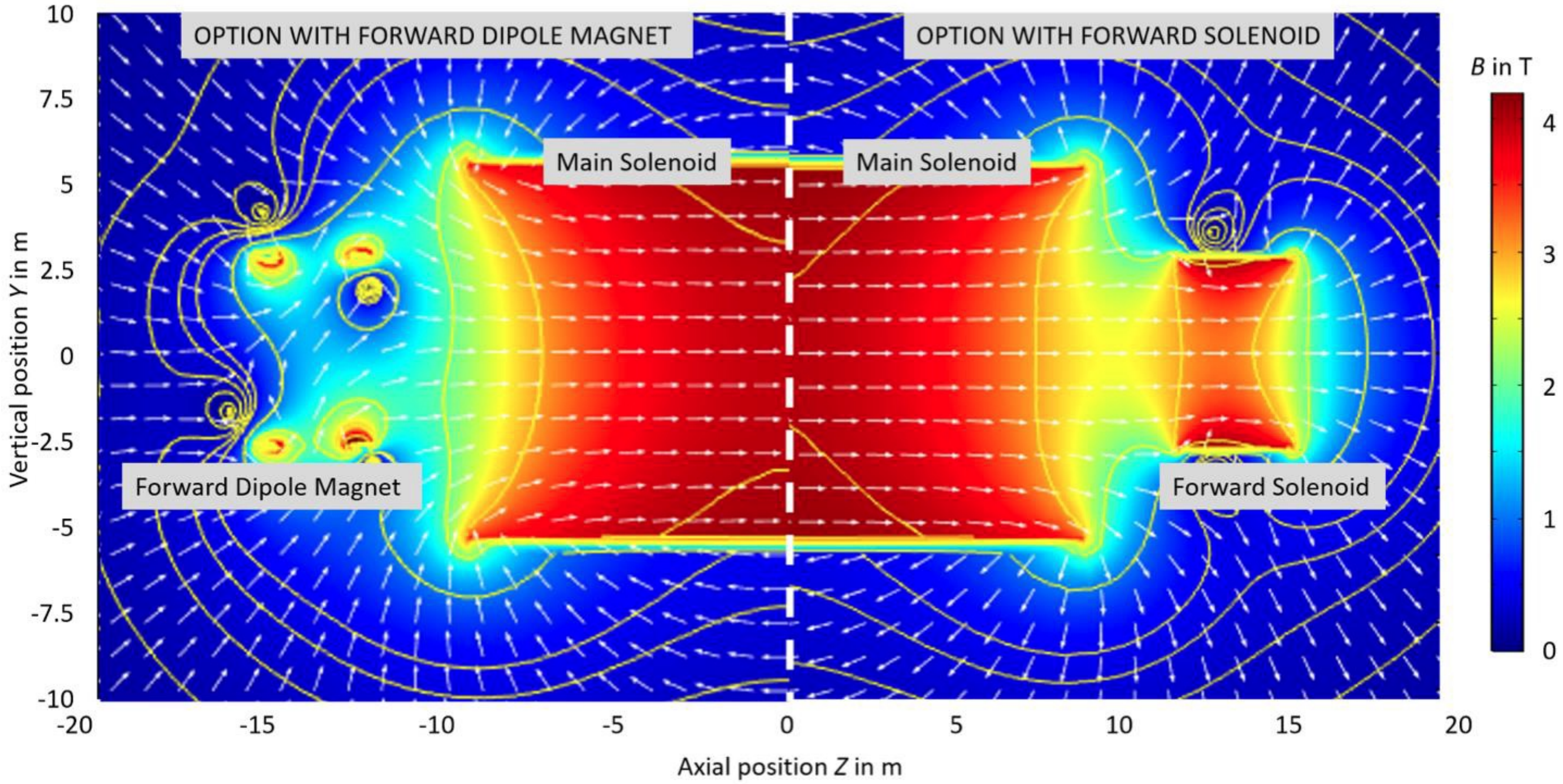
More forward overall … (in particular SM physics including W/Z/Higgs is very forward)



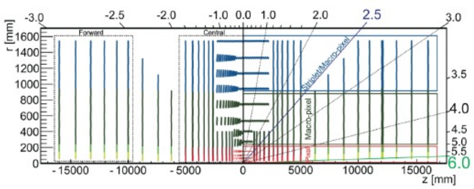
90% of 'heavy' physics will take place in η<2.5.

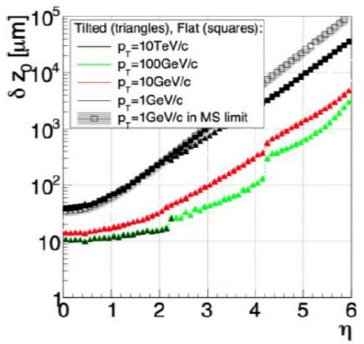
Increase of acceptance for precision spectroscopy and calorimetry from 2.5 at LHC to 3.8-4 for SM physics.

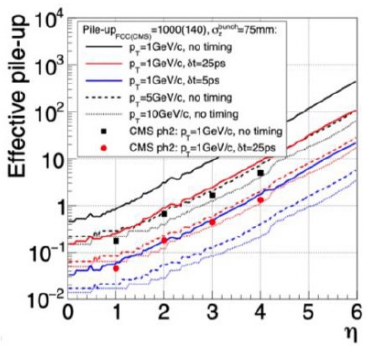
More magnetic spectrometers!



What resolution is needed?







Pileup, Timing, Tagging

Average distance between vertices at z=0:

1mm for HL-LHC (140 pileup)
125um for FCC-hh (1000 pileup)

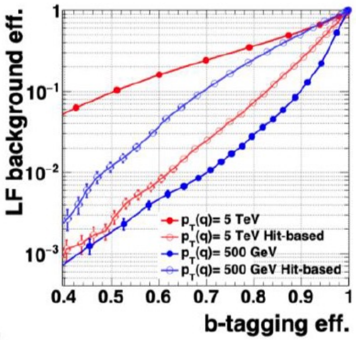
As for HL-LHC, timing can help for vertex identification:

Effective pileup:
Number of vertices that a track of a given p_T is compatible with at 95% CL.

For a time resolution of 25ps, CMS can get to an effective pileup of 1 for 1 GeV/c tracks at η = 4.

For an FCC detector the time resolution has to be at a level of 5ps to get to similar numbers.

The impact of pileup on a given physics analysis depends very much on the specific channels.



B-tagging studies:

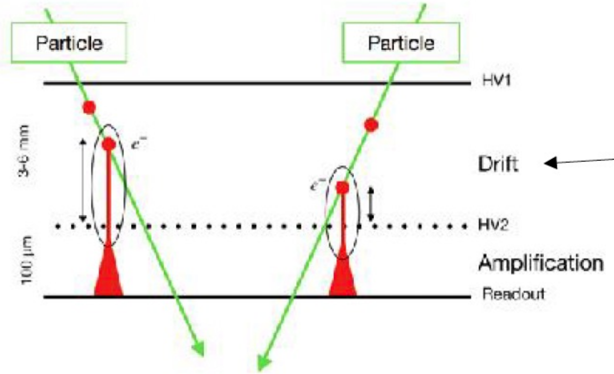
B-Mesons with very high p_T travel far into the tracker and have a highly collimated decay tracks.

Traditional taggers have difficulty in identifying the decay vertex.

Using the 'multiplicity jump' between tracking layers due to a b decay can significantly improve the tagging performance.

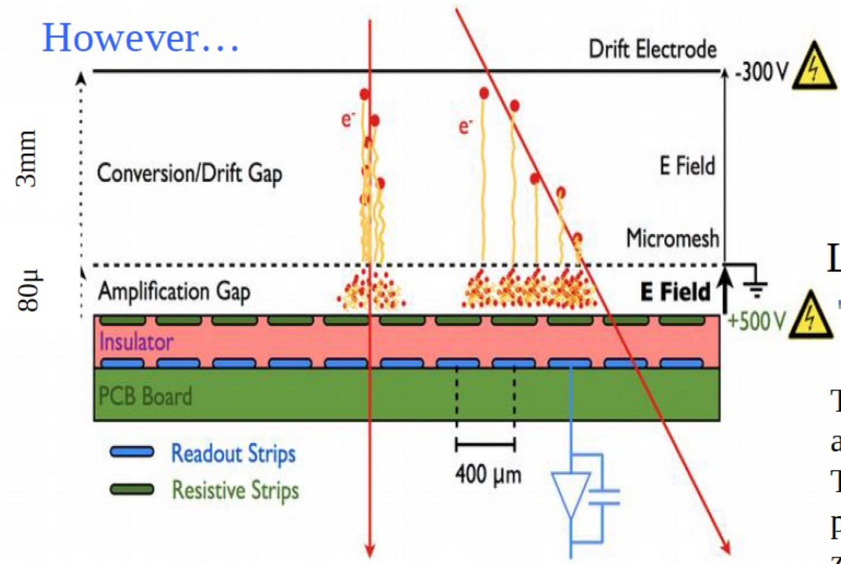
To reject pileup with timing need on the order of 5 ps timing!!

What limits the timing resolution



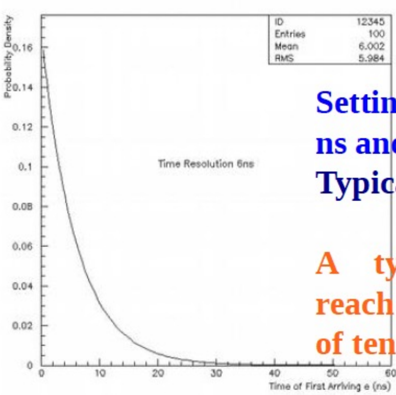
- Ionizations occur in different positions along the particle's trajectory → ~ ns time jitter for a 3-6 mm conversion region
- Diffusion effects

However…



Using the drift velocity (V), we express the probability that the first electrons will reach the anode at time t as

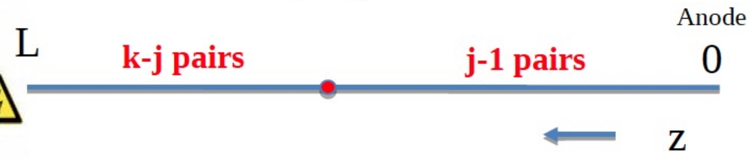
$$A^{n}_{first}(t) = n(V/L)e^{-nVt/L}$$



Setting typical values, i.e. V=50µm/ns and n=10 we conclude that: Typical Time Resolution ~6ns

A typical MicroMegas cannot reach timing resolution at the level of tenths of ps

$$P^{n}_{k} = \frac{n^{k}}{k!} e^{-n}$$



The probability that an e-ion pair has been produced at Z=z is the same for any value of Z; **p=1/L**

Then, in case that k pairs are produced, the probability that the jth pair has been produced at Z= z is given by the binomial distribution

$$D^{k}_{j}(x) = \frac{k!}{(k-j)!(j-1)!}(1-x)^{k-j}x^{j-1}$$

where **x=z/L describes the probability that a pair is produced in the region 0-z**

The probability that the jth pair has been produced at Z= z for any total number of e-ion pair

$$A^{n}_{j}(x) = \sum_{k=j}^{\infty} P^{n}_{k} D^{k}_{j}(x) = \frac{x^{j-1}}{(j-1)!} n^{j} e^{-nx}$$

The probability that the last pair (i.e. the closest to the edge 0) has been produced at Z= z is given by (j-1=0):

$$A^{n}_{last}(x) = ne^{-nx}$$

$$A^{n}_{last}(z) = ne^{-nz/L}$$

Ionization statistics place limits on the timing resolution of order ~5ns

The Physics of Ionization offers the means for precise spatial measurements (high spatial resolution) but inhibits precise timing measurements

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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PRINCIPLES OF OPERATION OF MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

Lectures given in the
Academic Training Programme of CERN
1975-1976

GENEVA
1977

which is represented in Fig. 8, for n = 34, as a function of the coordinate across a 10 mm thick detector. If the time of detection is the time of arrival of the closest electron at one end of the gap, as is often the case, the statistics of ion-pair production set an obvious limit to the time resolution of the detector. A scale of time is also given in the figure, for a collection velocity of 5 cm/μsec typical of many gases; the FWHM of the distribution is about 5 nsec. There is no hope of improving this time resolution in a gas counter, unless some averaging over the time of arrival of all electrons is realized.

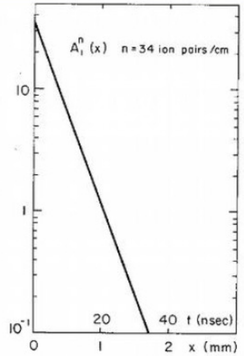
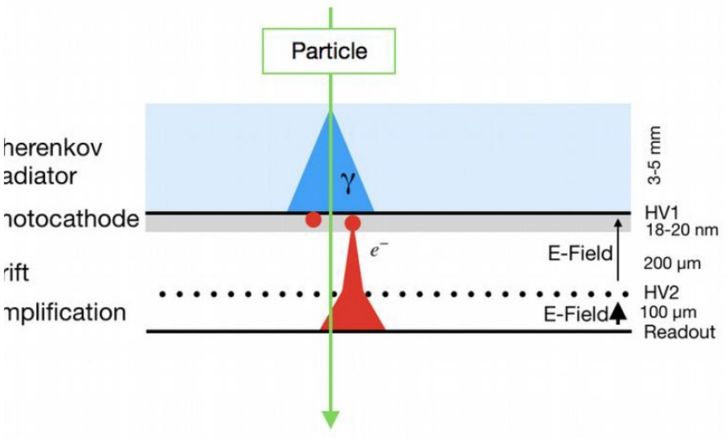


Fig. 8
Statistics of primary ion pair production: probability of finding the closest pair at a distance x from one electrode in a counter, in argon-isobutane 70-30. The corresponding electron minimum collection time is shown, for a typical drift velocity of electrons of 5 cm/μsec.

Ionzation detectors limited to about 5 ns!

The PICOSEC concept



Cherenkov radiator + Photocathode

- ✓ Particle produce Cherenkov light
- ✓ Photo-electrons emerge from photocathode
- ✓ Electrons amplified by a two-stage Micromegas

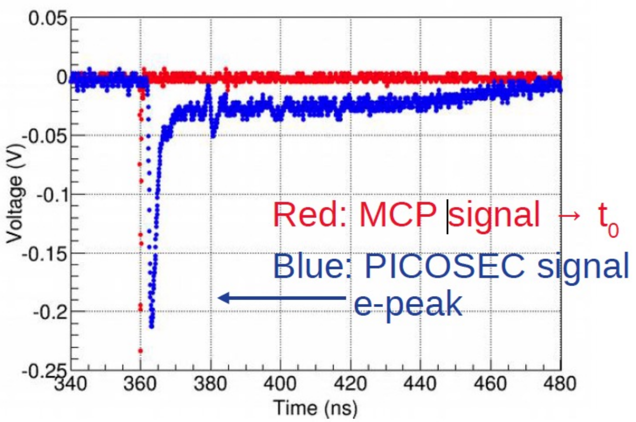
Signal components: Fast <1ns (electron peak) &
Slow ~100ns (Ion-tail)

Small drift gap (~200 μm) + High E-field:

- ✓ Pre-amplification possible
- ✓ Limited direct ionization
- ✓ Reduced diffusion impact

Cherenkov radiator:

- ✓ Photo-electrons emerging the photocathode simultaneously (fixed distance from the mesh)



Result: improved timing resolution

Beam tests: time resolution for MIPs

Same detector as for Laser tests:

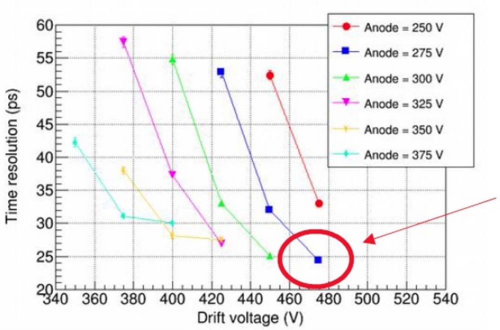
- MgF_2 radiator 3 mm thick
- 18 nm CsI on 5.5 nm Cr
- Bulk MicroMegas
- “COMPASS gas”

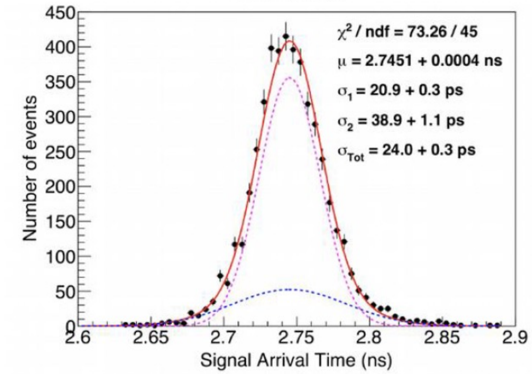
Optimum operation point: **V_{drift}/V_{anode}: -475V/+275V**

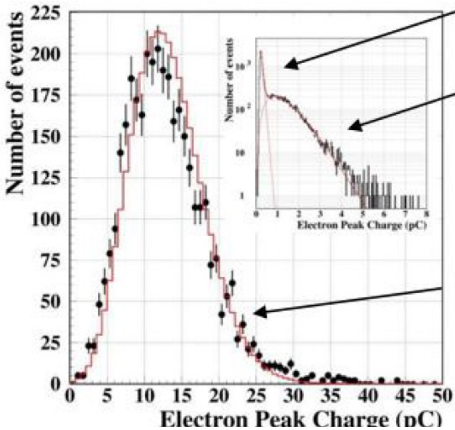
Best result: **24 ± 0.3 ps**

$N_{p.e.}$ = **10.1 ± 0.7**

Mean number of p.e. per muon produced in the CsI photocathode





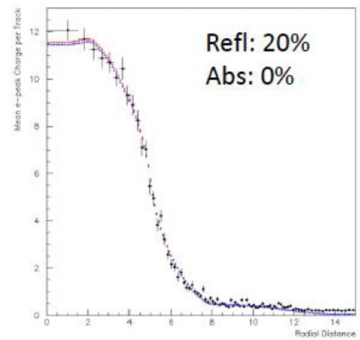


Noise component

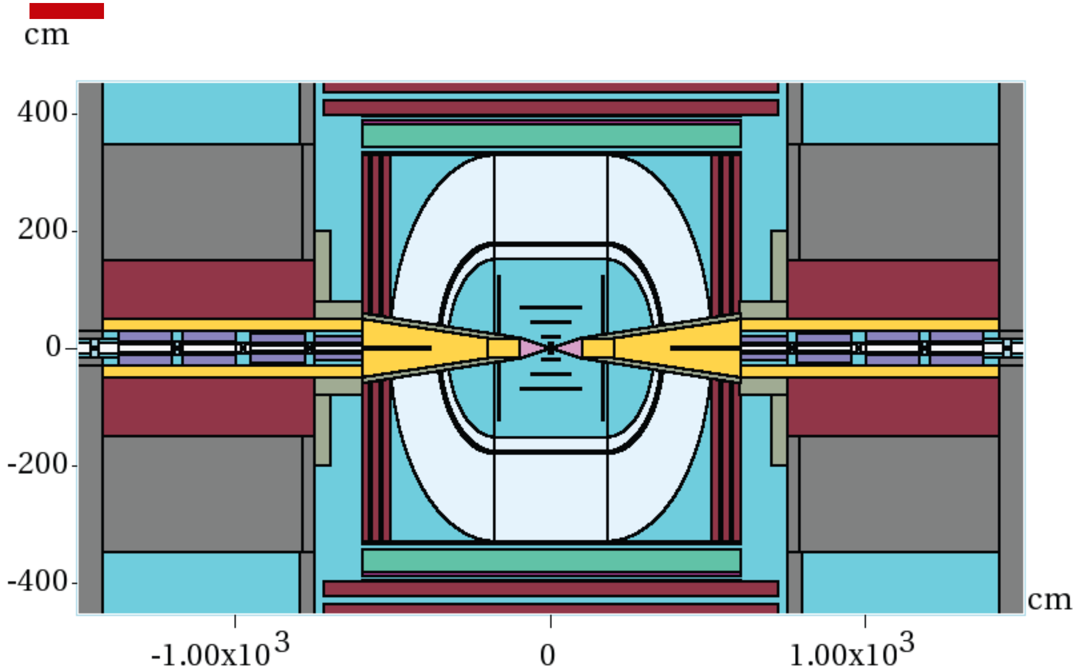
Signal for single p.e from UV-lamp tests: “Polya” (Gamma distribution)

Signal of MIPs

Convolution of Poisson, geometrical acceptance function and single p.e. response (Polya)

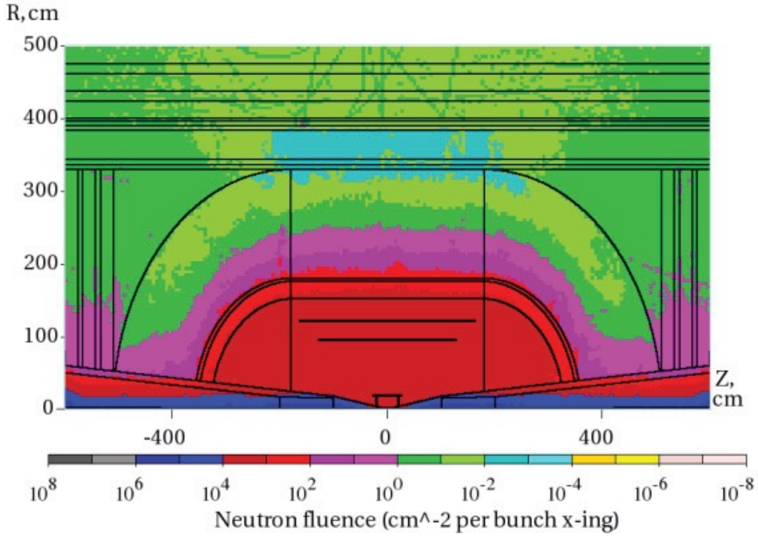


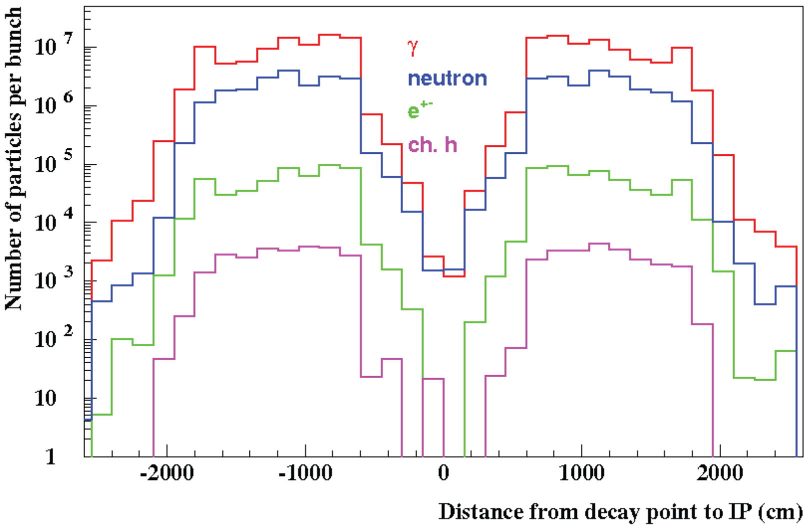
Muon detection at Muon Collider?



As noted by talk from Karri, large beam induced background
In forward region necessitates large forward sheilding

Large number of electrons, photons, neutrons from decay in flight and subsequent shower

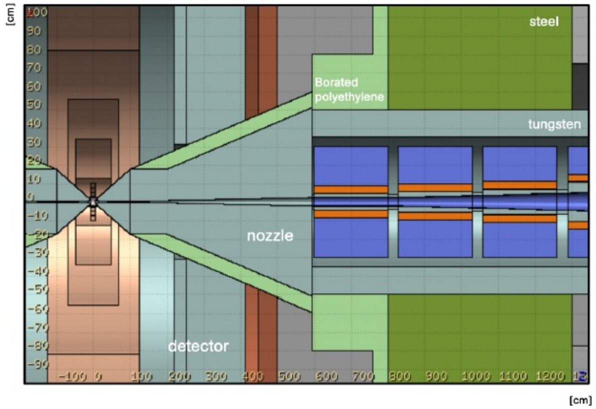




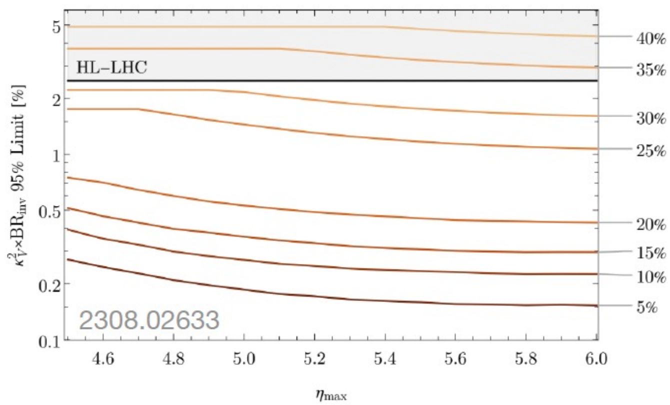
Silicon in the far forward region?

Work in progress: Forward Muon Tagging

Face of the nozzle: covers 3 < |η| < 6



Br(inv) sensitivity with different coverage and σ(E)/E assumptions



B-field & path-length for momentum measurement?
Effects of scattering/energy loss from ~2000 X_0 of Tungsten?
What technology can withstand BIB?

Summary

- Future muon detection will for the foreseeable future require instrumenting very large volumes of space
  - Difficult to get around using gas detectors for reason of cost
- Trending toward continued minimization of structures to minimize the distance between channels and improve the spatial resolution and novel new techniques

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