# Gas-based detectors

Most gas-based detectors rely on the same principles:

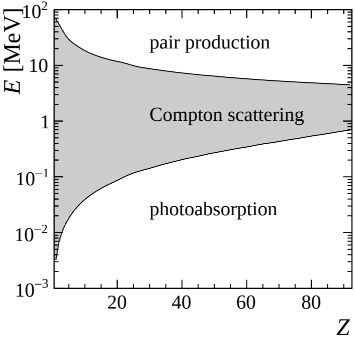
- a charged particle ionizes gas atoms/molecules along its track,
- an electric field transports electrons (and ions) towards electrodes,
- electrons are multiplied in a strong electric field,
- the moving electrons/ions induce a current on the readout electrodes.

- Most examples on the following slides focus on argon, which is a commonly used detection gas.
- Its ionization potential is 15.7 eV.
- Typically, it is used with an admixture of a "quenching gas" (*e. g.* $CH_4$ or $CO_2$).

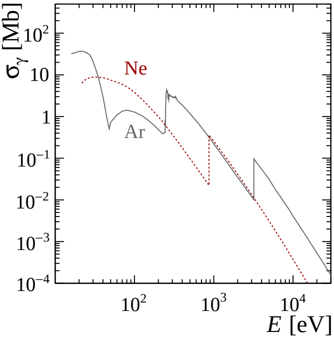
## Why argon?

- Third most common gas in the atmosphere (0.93%).
- Cheap (produced commercially by the distillation of liquid air).
- Inert (noble gas).
- Safe (non-toxic, non-flammable, . . . ).

# Reminder: photon interactions



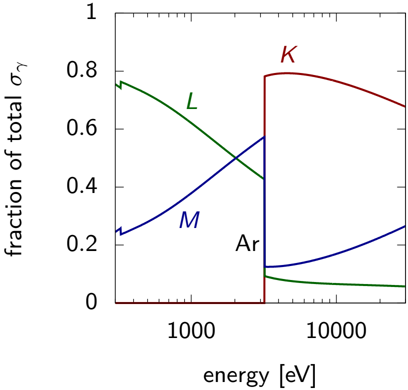
# Photoabsorption



Photoabsorption cross-section $\sigma_\gamma$ of neon and argon.

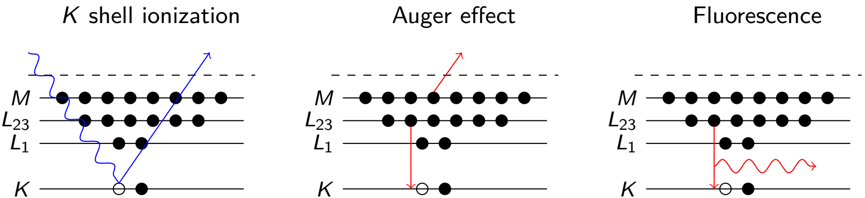
## Example: 5.9 keV $\gamma$ in Ar

- $\sigma_\gamma \sim 0.019\,\mathrm{Mbarn}$
- Absorption length at room temperature, atm. pressure: $\lambda \sim 2\,\mathrm{cm}$

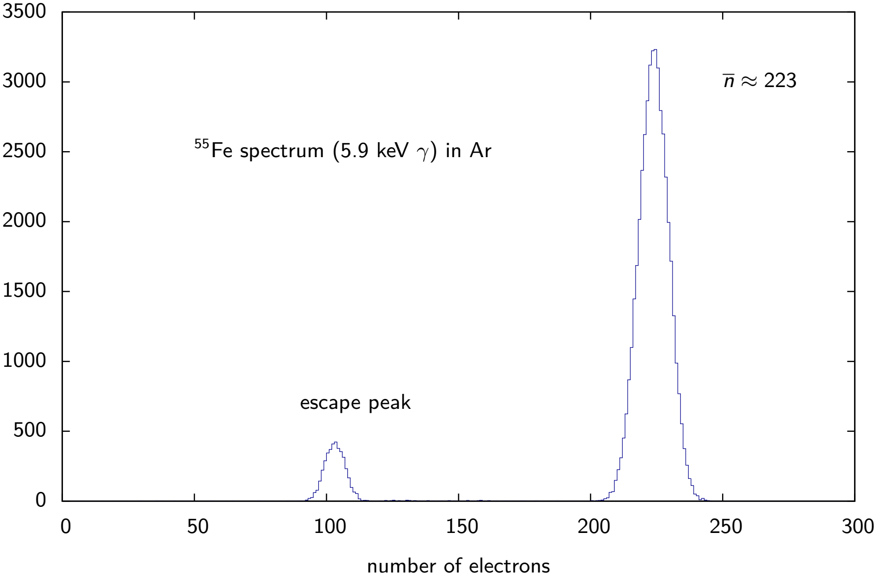


D. A. Verner *et al.*, At. Data Nucl. Data Tables **55** (1993), 233-280

- The ionization of inner shells is followed by atomic relaxation processes, resulting in the emission of Auger electrons and fluorescence photons.



- The fluorescence yield (probability to fill a vacancy radiatively) increases with the atomic number $Z$.
- Depending on their energy, the emerging photoelectrons and Auger electrons can ionize and excite additional gas atoms along their path and produce secondary electrons.



3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
number of electrons
$^{55}$Fe spectrum (5.9 keV $\gamma$) in Ar
$\overline{n} \approx 223$
escape peak

# $W$ value and Fano factor

- Mean number of electrons:

$$\overline{n} = \frac{E_\gamma}{W}$$

- Variance:

$$\sigma^2 = F\overline{n}$$

| Gas | $W$ [eV] | $F$ |
|---|---|---|
| Ne | 35.4 | 0.13 - 0.17 |
| Ar | 26.4 | 0.16 |
| Xe | 22.1 | 0.17 |
| $CO_2$ | 33.0 | 0.32 |
| $CH_4$ | 27.3 | 0.26 - 0.29 |

ICRU Technical Report 31 (1979)
IAEA TECDOC 799 (1995)

The interaction of **charged particles** with a gas is described by the differential cross-section $\mathrm{d}\sigma/\mathrm{d}E$, where $E$ is the energy transfer in a collision.

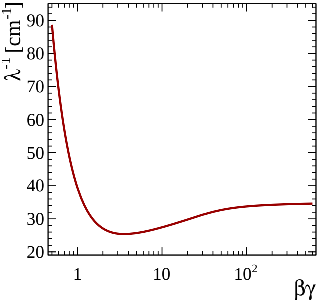
- Average number of collisions per cm (cluster density):

$$\lambda^{-1} = N \int_{0}^{E_{\max}} \mathrm{d}E \, \frac{\mathrm{d}\sigma}{\mathrm{d}E}$$

- Average energy loss per cm (stopping power):

$$\frac{\mathrm{d}E}{\mathrm{d}x} = N \int_{0}^{E_{\max}} \mathrm{d}E \, \frac{\mathrm{d}\sigma}{\mathrm{d}E} E$$

# Cluster density



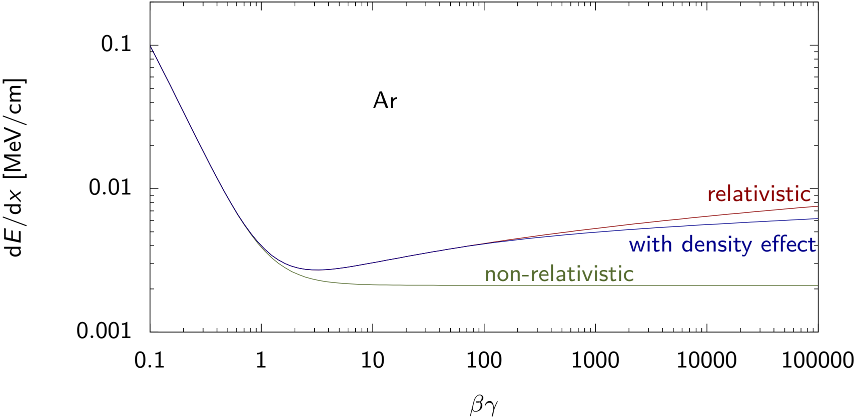
Cluster density in Ar at 20° C, 1 atm.

Measurements with "minimum ionizing" electrons:

| Gas | $\lambda^{-1}$ [cm$^{-1}$] |
|---|---|
| Ne | 11 |
| Ar | 23 |
| Xe | 43 |
| $CO_2$ | 34 |
| $CH_4$ | 25 |

F. Rieke and W. Prepejchal,
Phys. Rev. A **6** (1972), 1507-1519

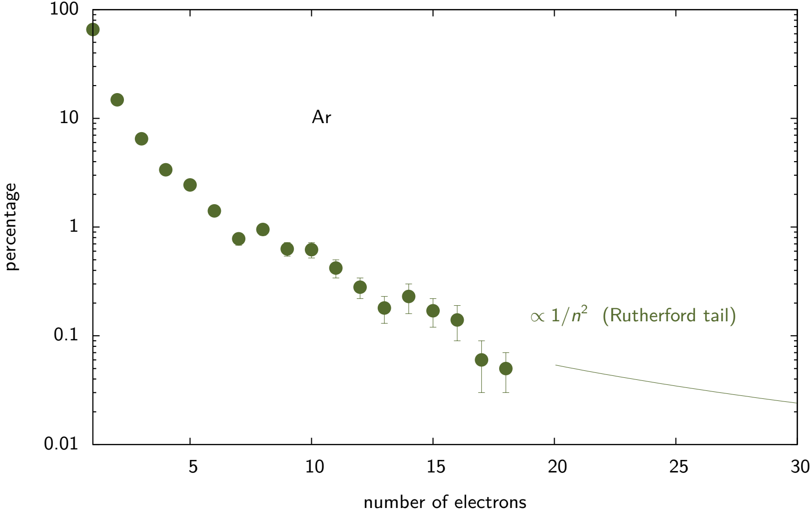
# Stopping power: Bethe-Bloch formula



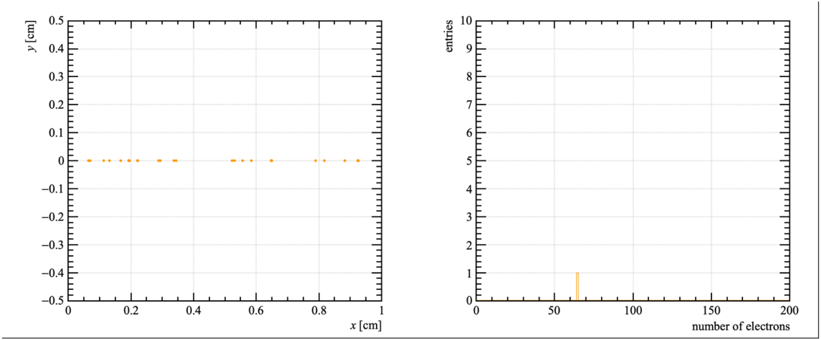
$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{4\pi z^2 e^4}{mc^2} NZ \frac{1}{\beta^2}\left[\ln\frac{2mc^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right].$$

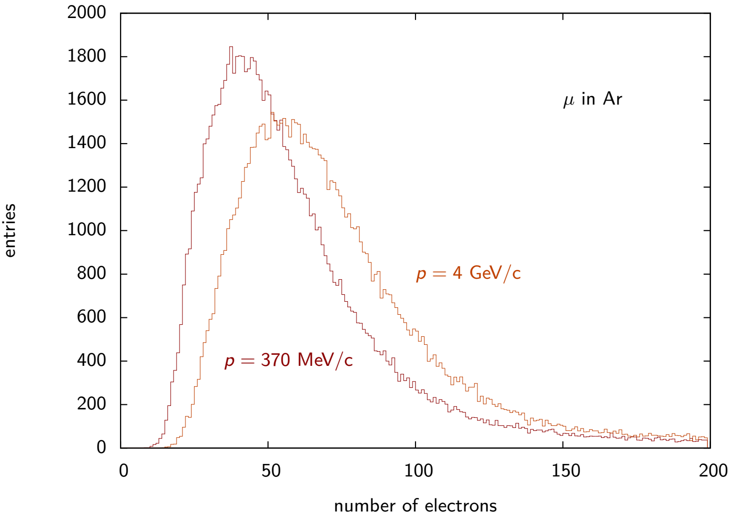
The number of electron/ion pairs deposited in the gas will fluctuate from track to track because of fluctuations

- in the number of collisions a particle suffers over a distance $x$ (follows a Poisson distribution around $x/\lambda$), and
- in the number of electron/ion pairs produced in a each collision ("cluster size").



Cluster size distribution in Ar. H. Fischle *et al.*, NIM A **301** (1991), 202-214


y [cm]
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
0
0.2
0.4
0.6
0.8
1
x [cm]
entries
10
9
8
7
6
5
4
3
2
1
0
0
50
100
150
200
number of electrons

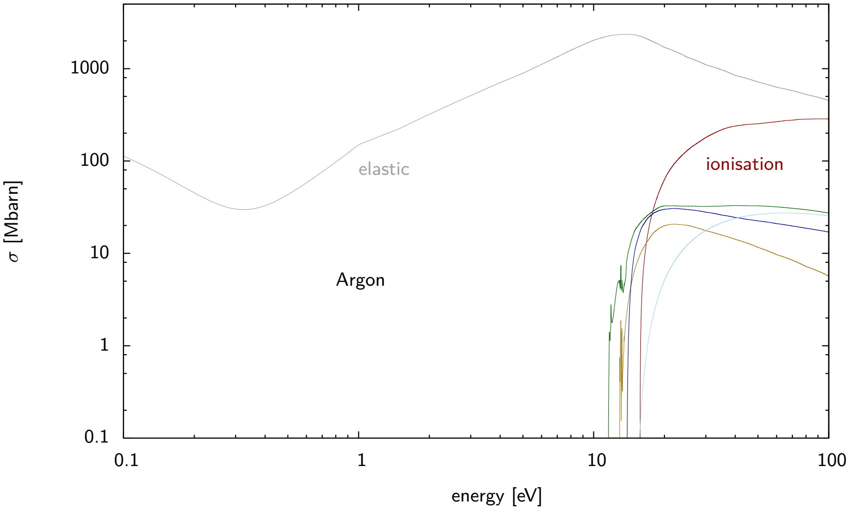


Number of ionization electrons in a 1 cm layer of Ar.

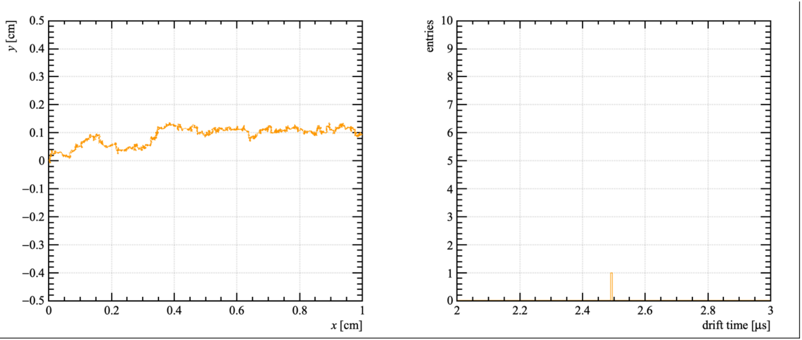
- To detect the electrons and ions produced in the gas by the passage of a charged particle, we need to move them by applying an electric field.

## Electron transport

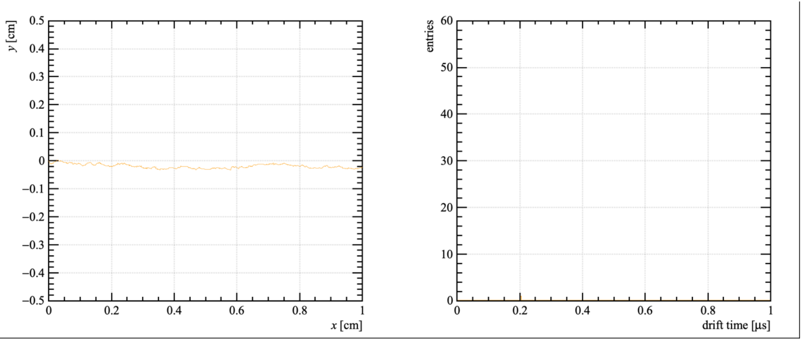
- The microscopic motion of an electron in a gas is a stochastic process.
- At atmospheric pressure, the mean free path between collisions of an electron with a gas atom/molecule is of order $0.1 \ldots 1\,\mu\text{m}$.
- Between collisions, the electron is accelerated by the electric field.
- In a collision, an electron may transfer part of its energy to the atom/molecule and/or change direction.
- To design a detector, we need to know (among other things) the average macroscopic drift velocity of an electron at a given electric field.
- We are also interested in how much individual electrons deviate from the average (diffusion).

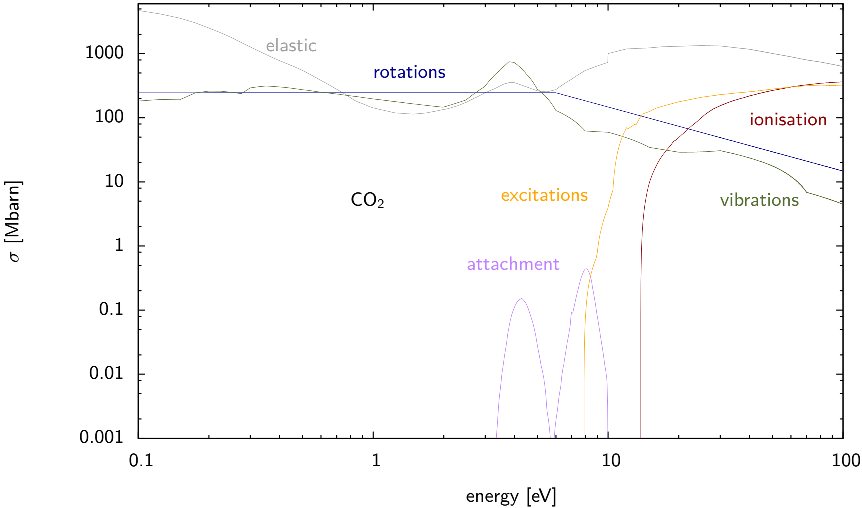

1000
100
10
1
0.1
σ [Mbarn]
0.1
1
10
100
energy [eV]
elastic
ionisation
Argon

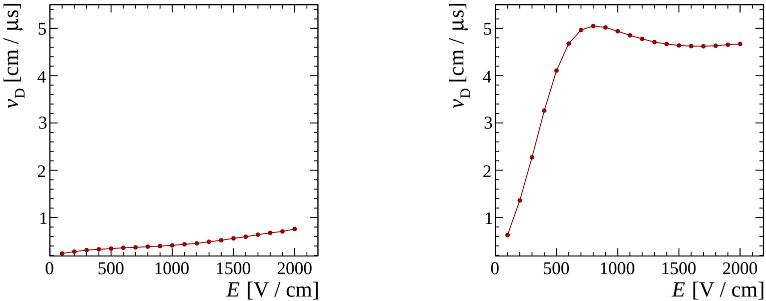
- Pure argon, $E = 1\,\mathrm{kV}\,/\,\mathrm{cm}$



- Ar/$CO_2$ (90:10), $E = 1\,\mathrm{kV}\,/\,\mathrm{cm}$

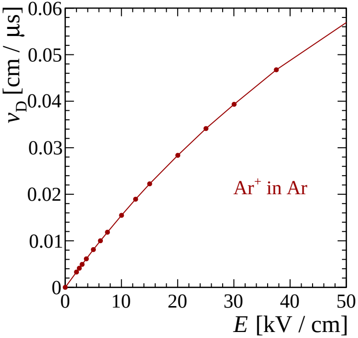



elastic
rotations
ionisation
excitations
vibrations
attachment
$CO_2$
1000
100
10
1
0.1
0.01
0.001
$\sigma$ [Mbarn]
0.1
1
10
100
energy [eV]



Electron drift velocity in pure argon (left) and Ar/$CO_2$ 90:10 (right).

# Ion transport

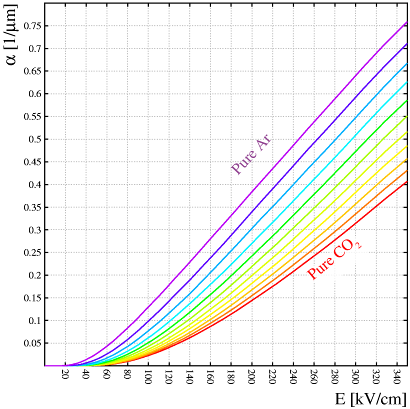


## Gain

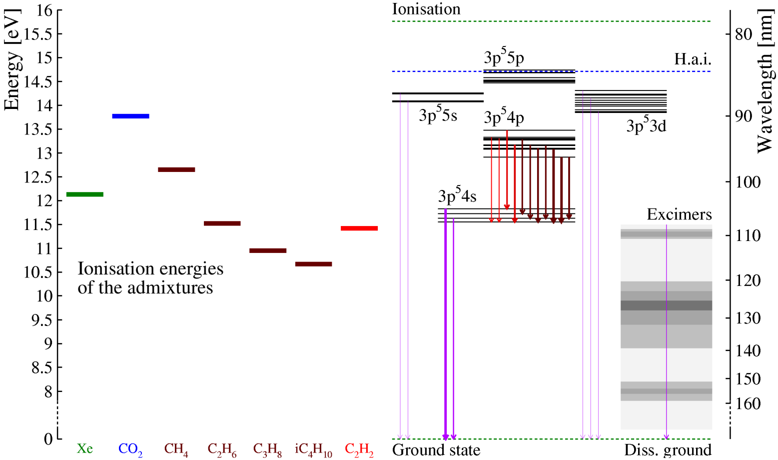
- The amount of charge produced by a charged particle crossing a gas detector is usually too small to be measured directly ($40\,\mathrm{e}^- \sim 6.4 \times 10^{-3}\,\mathrm{fC}$).
- We need to amplify the signal by creating secondary avalanche electrons in a strong electric field (few tens of kV / cm).
- The avalanche growth is characterised by the Townsend coefficient $\alpha$,

$$\mathrm{d}n = n\alpha \mathrm{d}x$$

- In a constant electric field, the gas gain is given by $\exp(\alpha x)$.

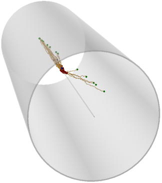


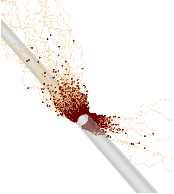
- The above plot (stolen from Rob Veenhof) shows the Townsend coefficient for Ar/$CO_2$ mixtures, calculated using the Magboltz program.
- Does the calculated gain of the gas mixture match measurements?

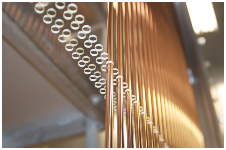

Energy [eV]
16
15.5
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
0
Xe
$CO_2$
$CH_4$
$C_2H_6$
$C_3H_8$
$iC_4H_{10}$
$C_2H_2$
Ionisation energies
of the admixtures
Ionisation
$3p^55p$
H.a.i.
$3p^55s$
$3p^54p$
$3p^53d$
$3p^54s$
Excimers
Ground state
Diss. ground
Wavelength [nm]
80
90
100
110
120
130
140
150
160

## Penning transfer

- Argon has excited states above the ionization energy of typical admixtures, including $CO_2$ (13.78 eV ionization energy).
- With a certain probability, the energy of such excited states can be transformed into ionization of the admixture.
- This process (Penning effect), can contribute significantly to the effective gain of gas mixtures.





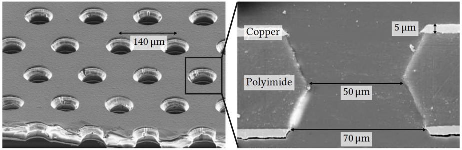


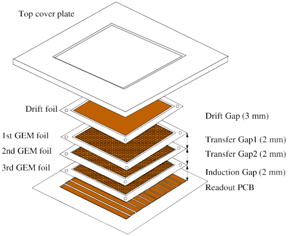
## How to create a strong electric field?

- One technique (going back to the Geiger counter) is to use a wire ($1/r$ dependence of the electric field).
- Wire-based chambers (MWPC, drift chambers, straw tubes, …) are still widely used today, but they have limitations in terms of particle rate and track density.
- This motivated the development of detectors with finer granularity (cell size of order 100 µm), profiting from advances in photolithography: Micropattern Gas Detectors (MPGD).

# Gaseous Electron Multiplier (GEM)

- Thin metal-clad polymer foil, with a regular, high-density pattern of chemically etched holes.
- Applying a potential difference between the metal layers creates a high-field amplification region in the holes.
- To achieve gains of order $10^4 - 10^5$, one often puts multiple (typically three) GEMs in series.
- GEMs are used *e. g.* in the CMS muon system and in the ALICE TPC.

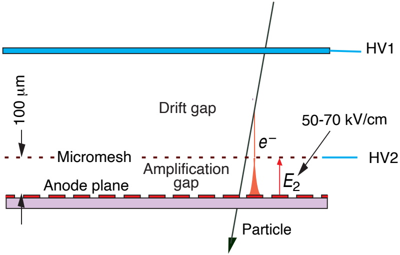


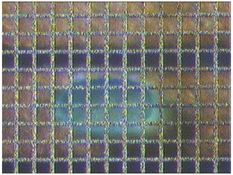


Movie

# Micromegas

- Consists of an amplification gap (few tens of kV / cm, 50 – 150 µm) and a drift gap (∼ kV / cm).
- The two regions are separated by a micromesh (∼ 15 µm wires) supported by pillars.
- Ionization electrons produced in the drift gap are funneled into the amplification gap by the high ratio of electron fields between the two gaps.
- Micromegas are used, for instance, in the ATLAS muon system.





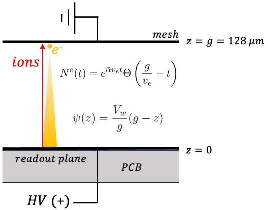
## Induced signals

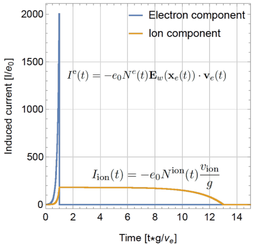
- Recap: motion of charges (electrons/ions) in the gas induces a current on the readout electrodes.
- To calculate the induced current, we use the Ramo-Shockley theorem

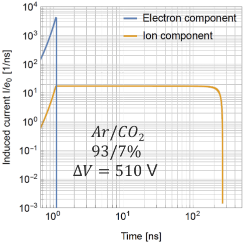
$$i(t) = q\mathbf{v} \cdot \mathbf{E}_w$$

  where $E_w$ is the so-called weighting field.
- To calculate the weighting field, we apply 1 V to the readout electrode and ground all other electrodes.
- In a parallel-plate chamber (gap $d$), the weighting field is constant ($E_w = 1/d$).

# Signal in a Micromegas







Slide stolen from Djunes Janssens.