

Gaseous detectors principles and performance comparison

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Strating from the basics

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- ▶ Any radiation detector exploits the physics of the interaction of radiation with matter to achieve the quantum decoherence (old: collapse of the quantum wave function).
- ▶ the release of electromagnetic energy can be detected by a transducer
- ▶ In order to have a sufficient S/N i.e. to discriminate a signal above the random electronic fluctuations of the readout, the original signal, made of light or moving electrons is transferred to an amplification element
- ▶ Amplification is obtained by a combination of the following ways:
 - ▶ By an amplifying physical process within the detector structure
 - ▶ By an electronic amplifier
- ▶ Any radiation detector couples a sample of matter as target, a transport mechanism and a transduction and amplification structures.
- ▶ Gaseous detector are characterized by using a gaseous target...
- ▶ The many types of gaseous detectors are differentiated by transport, transduction and amplification structures...



Why gaseous detectors?

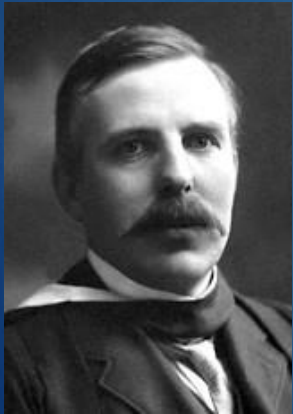
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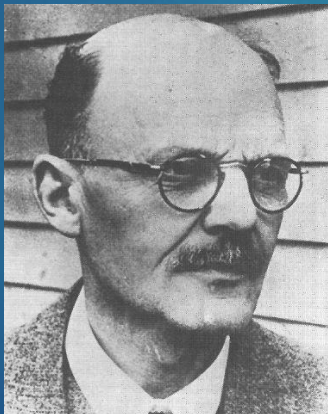
- ▶ Technologically simpler than other solid state detectors, in facts they have been the first single particle detector “in real time” (Geiger counter 1908)
- ▶ Gas can be replaced so the target is not subject to deterioration
- ▶ They can be shaped easily in very different ways
- ▶ They can have very large and continuous targets (true also for liquid target detectors which are close relatives of gaseous detectors...)
- ▶ They cost for unit surface or volume is low compared to other technologies
- ▶ For the characteristics above they have been used successfully in large spectrometers and tracking systems
- ▶ One iconic type the MWPC was awarded with Nobel Prize ☺ (Charpak 1992)

The ancestor: the Geiger counter

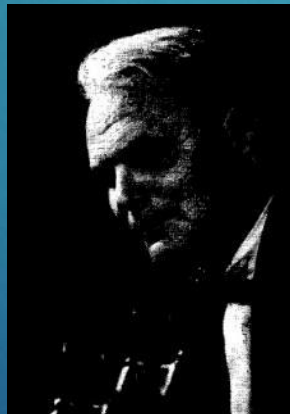
- It contains all the element of the list in slide 2 (see later)
- Detects radiation by electron discharge;
- can count α , β and γ particles (at low rates ...)
- 1908: Ernest Rutherford and Hans Geiger
- 1928: Hans Geiger and Walther Müller
- 20 years from ideation to a versatile implementation



Ernest Rutherford
(1871-1937)



Hans Geiger
(1882-1945)



Walther Müller
(1905-1979)



A Geiger-Müller counter built in 1939 and used in the 1947-1950 for cosmic ray studies in balloons and on board B29 aircraft by Robert Millikan et al.

Made of copper, 30 cm long

Motivation for the Geiger counter

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In considering a possible method of counting the number of α -particles, their well-known property of producing scintillations in a preparation of phosphorescent zinc sulphide at once suggests itself.

The doubt, however, at once arises whether every α -particle produces a scintillation, for it is difficult to be certain that the zinc sulphide is homogeneous throughout. No confidence can be placed in such a method of counting the total number of α -particles (except as a minimum estimate),

It has been recognised for several years that it should be possible by refined methods to detect a single α -particle by measuring the ionisation it produces in its path.

We then had recourse to a method of automatically magnifying the electrical effect due to a single α -particle. For this purpose we employed the principle of production of fresh ions by collision. In a series of papers, Townsend* has worked out the conditions under which ions can be produced by collisions with the neutral gas molecules in a strong electric field. The effect is best shown in gases at a pressure of several millimetres of mercury.

* 'Phil. Mag.,' February, 1901 ; June, 1902 ; April, 1903 ; September and November, 1903.

- Interesting story:
- The authors successfully used phosphorescence in the famous Rutherford experiment
- They found out the limits and that something new was needed to really progress
- Made use of the new physics of electron multiplication at low pressure as discovered a few years before in 1901 by JS Townsend.

[E. Rutherford and H. Geiger, *An Electrical Method of Counting the Number of α -Particles from Radio-Active Substances*, Proc. R. Soc. Lond. A **81** (1908) 141-161]

Overview of the physics principles

A notable template

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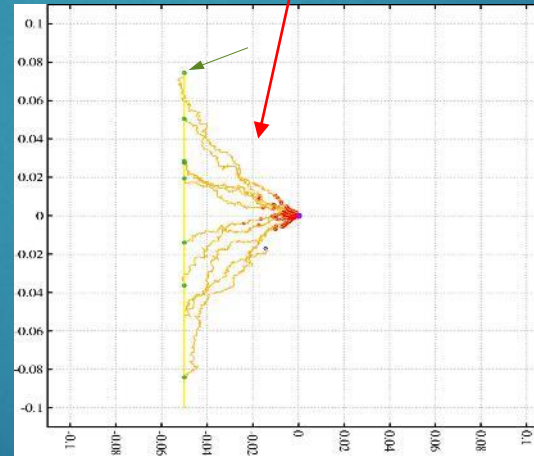
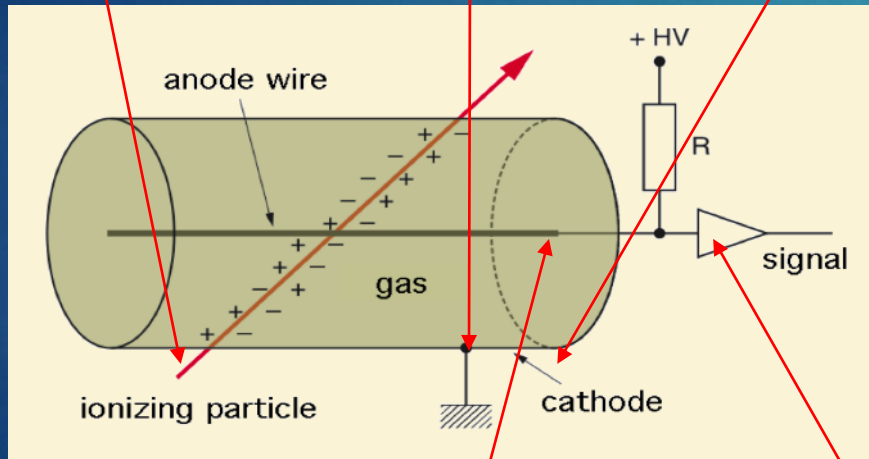
- Any radiation detector exploits the physics of the interaction of radiation with matter

incident radiation

Material target

Energy deposit

Transport and amplification



Radiation ionize the gas atoms, their number proportional to dE/dx of the particle

- In presence of an applied electric field in the gas volume electron drift at about 10^3 higher speed than ions
- With wire as anode and cylinder as cathode the field is:

$$E(r) = \frac{1}{r} \frac{V}{\ln(b/a)}$$

r ... distance from the wire
 a ... radius of anode wire
 b ... radius of cathode cylinder

- Close to the wire the field grows and the electron multiplication starts
- Signal is induced between anode and cathode by the moving electrons -> current is conserved... $i(t) = N(t)ev$ at any instant

Trans-duction

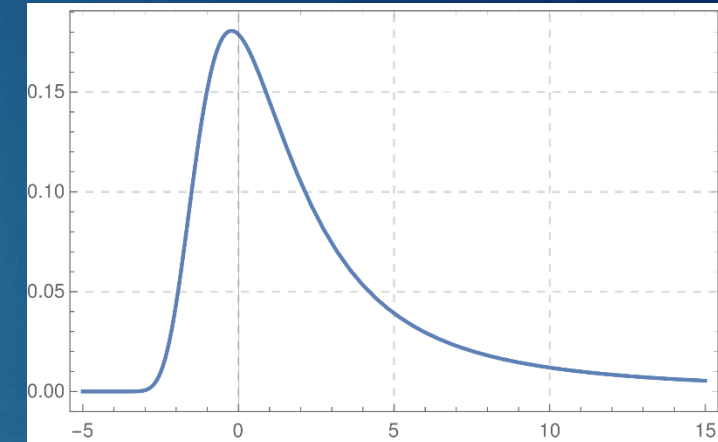
Electronic amplification

PRIMARY AND SECONDARY IONIZATION

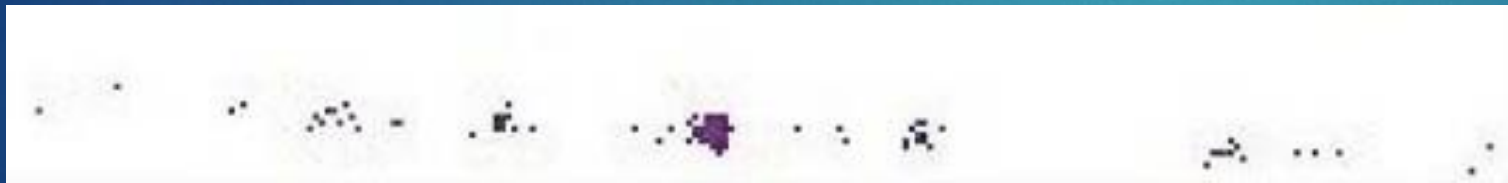
- Primary ionization: a charged particle deposits energy by ionizing the gas molecules
- The position of the ionization points is described by the Poisson statistics:

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

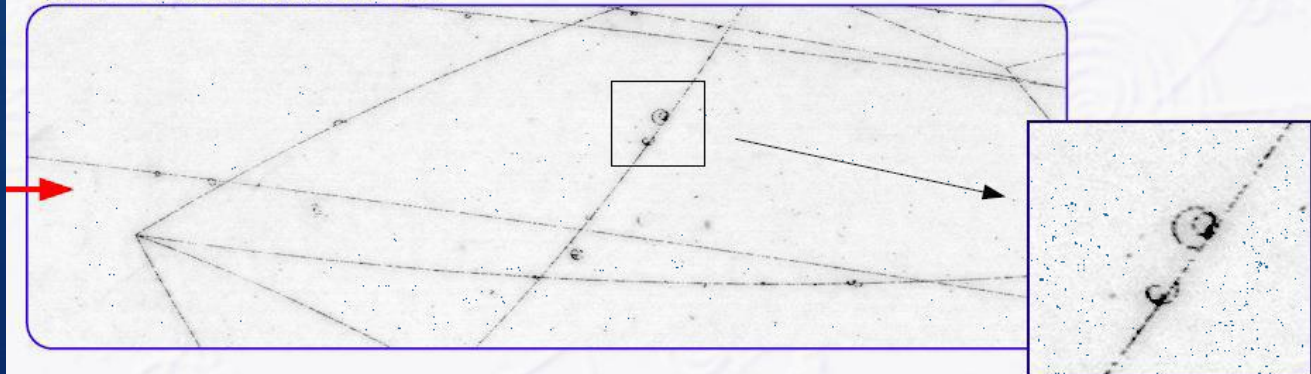
- $\langle n_p \rangle$ is the number of expected points per unit length
- The total energy deposited has a wide distribution (typically modelled with the Landau distribution) so the primary electron can generate secondary electrons → Total ionization per unit length > primary ionization per unit length



The Landau distribution describes the energy loss of fast, charged particles passing through thin layers of matter due to ionization. It is characterized by a narrow peak and a long high-energy tail caused by rare, large energy transfers, making the distribution asymmetric.



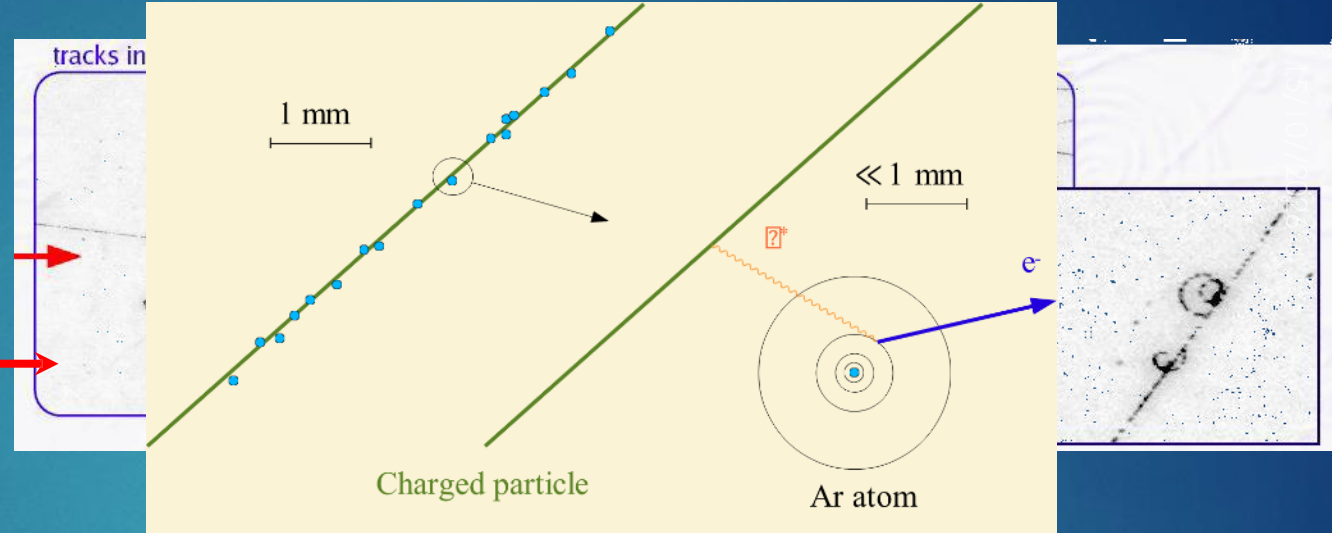
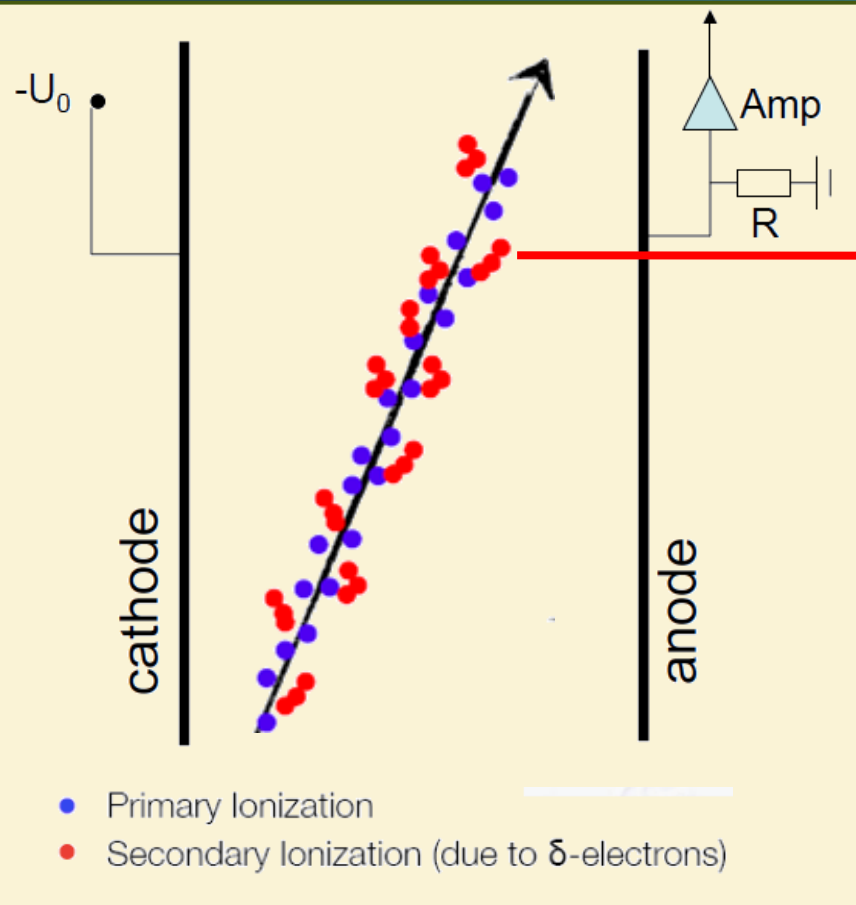
tracks in CERN 2m bubble chamber



Electrons are not evenly spaced, not even exponentially

PRIMARY AND SECONDARY IONIZATION

- An important fraction of the electron/ion pairs is from δ -electrons: **knocked-out through a virtual photon exchange**



- Example: Ar at normal pressure: A energy of $1 \text{ cm} \cdot dE/dx = 2.44 \text{ keV}$ creates 29.4 e/ion pairs per cm (83 eV/pair). Secondary ionization accounts for the difference to 94 pairs/cm ($\times 3!$), such that the average energy to create an e/ion pair is $w_i = 26 \text{ eV}$ (See next slide).

Gaseous detectors parameters

Gas	Z	A	ρ (g/cm ³)	E_{ex} (eV)	E_{ion} (eV)	I (eV)	w_i (eV)	$dE/(\rho dx)$ (MeV cm ² /g)	dE/dx (keV/cm)	n_p (cm ⁻¹)	n_{tot} (cm ⁻¹)	X_0 (m)
H ₂	2	2	$8.38 \cdot 10^{-5}$	10.8	15.4	19.2	37	4.03	0.34	5.2	9.2	7522
He	2	4	$1.66 \cdot 10^{-4}$	19.8	24.5	41.8	41	1.94	0.32	5.9	7.8	5682
N ₂	7	28	$1.17 \cdot 10^{-3}$	8.1	15.6	82	35	1.68	1.96	(10)	56	325
O ₂	8	32	$1.33 \cdot 10^{-3}$	7.9	12.1	95	31	1.69	2.26	22	73	257
Ne	10	20.2	$8.39 \cdot 10^{-4}$	16.6	21.6	137	36	1.68	1.41	12	39	345
Ar	18	39.9	$1.66 \cdot 10^{-3}$	11.5	15.8	188	26	1.47	2.44	29.4	94	118
Kr	36	83.8	$3.49 \cdot 10^{-3}$	10.0	14.0	352	24	1.32	4.60	31.6	192	33
Xe	54	131.3	$5.49 \cdot 10^{-3}$	8.4	12.1	482	22	1.23	6.76	44	307	15
CO ₂	6,8	44	$1.86 \cdot 10^{-3}$	5.2	13.8	85	33	1.62	3.01	35.5	91	183
CH ₄	6,1	16	$0.71 \cdot 10^{-3}$	9.8	15.2	41.7	28	2.21	1.48	25	53	646
C ₂ H ₆	6,1	30	$1.34 \cdot 10^{-3}$	8.7	11.7	45.4	27	2.30	1.15	41	111	340
i-C ₄ H ₁₀	6,1	58	$2.59 \cdot 10^{-3}$	6.5	10.6	48.3	23	1.86	5.93	84	195	169
CF ₄	6,9	88	$3.78 \cdot 10^{-3}$	12.5	15.9	115	34.3	1.69	7	51	100	92
C ₂ H ₆ O (DME)	6,1,8	46	$2.2 \cdot 10^{-3}$	6.4	10.0	60	23.9	1.77	3.9	55	160	222

- E_{ex} ... excitation energy threshold
- E_{ion} ... ionisation threshold
- w_i ... average energy to create an e⁻/h⁺ pair
- I ... average Ionization energy (Bethe Bloch)
- n_p, n_{tot} ... primary /total ionisations per cm (difference because of δ -electrons)
- w_i ... average energy to create an e/h pair
- X_0 ... radiation length
- DME ... Dimethylether

Diffusion

- In the **absence** of an **external field** the electrons and ions **diffuse** around the release point driven by Brownian motion
- The electrons and ions loose energy by multiple scattering until thermal equilibrium is reached

$$v_{\text{diff}} = \sqrt{\frac{8 k T}{\pi m}}$$

- e- $v_{\text{diff}} \approx 10^6 \text{ cm/s} = 10 \text{ } \mu\text{m/ns}$
ions $v_{\text{diff}} \approx 10^4 \text{ cm/s}$

- The diffusion coefficient is determined by the **average free path length** λ of e- and ions in the gas:

$$D = \frac{1}{3} v_{\text{diff}} \lambda$$

$$\lambda = \frac{1}{\sqrt{2}} \frac{k T}{\sigma p}$$

p ... gas pressure, T ... temperature,

k ... Boltzmann constant, $k = 1.3807 \cdot 10^{-23} \text{ J/K}$

σ ... total cross section for collision with a gas molecule

- Solving the Boltzman equation for a initial point-like ionization deposit, the charge carrier distribution evolves as a time-dependent Gaussian (projected in 1D)

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

from where one can extract the width σ_x and the volume diffusion

$$\sigma_x = \sqrt{2Dt}$$

$$\sigma_{\text{vol}} = \sqrt{3} \cdot \sigma_x = \sqrt{6Dt}$$

Drift in electric field

- If an **external electric field** is applied the electrons and ions are accelerated and move along the field lines → a **drift** is induced
 - The drift is **superimposed** onto the diffusion movement
- Acceleration is interrupted by collision with gas atoms, this limits the drift velocity.
- The mean drift velocity v_D is

$$\vec{v}_D = \frac{q}{m} \cdot \tau(\vec{E}, \sigma) \cdot \vec{E} \cdot \frac{p_0}{p} = \mu \cdot \vec{E} \cdot \frac{p_0}{p}$$

where

q, m ... charge and mass

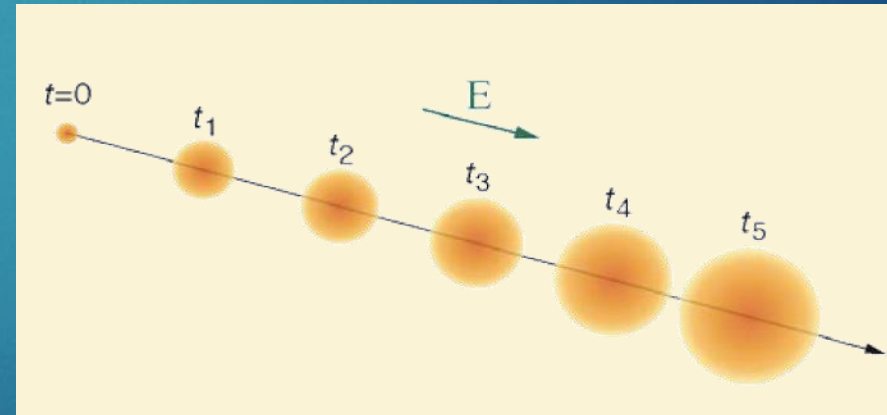
E ... electric field

τ ... mean time between collisions

p ... gas pressure, p_0 ... standard pressure

μ ... mobility, $\mu = \tau \cdot q/m$,

and typical values 10-100 $\mu\text{m/ns}$.

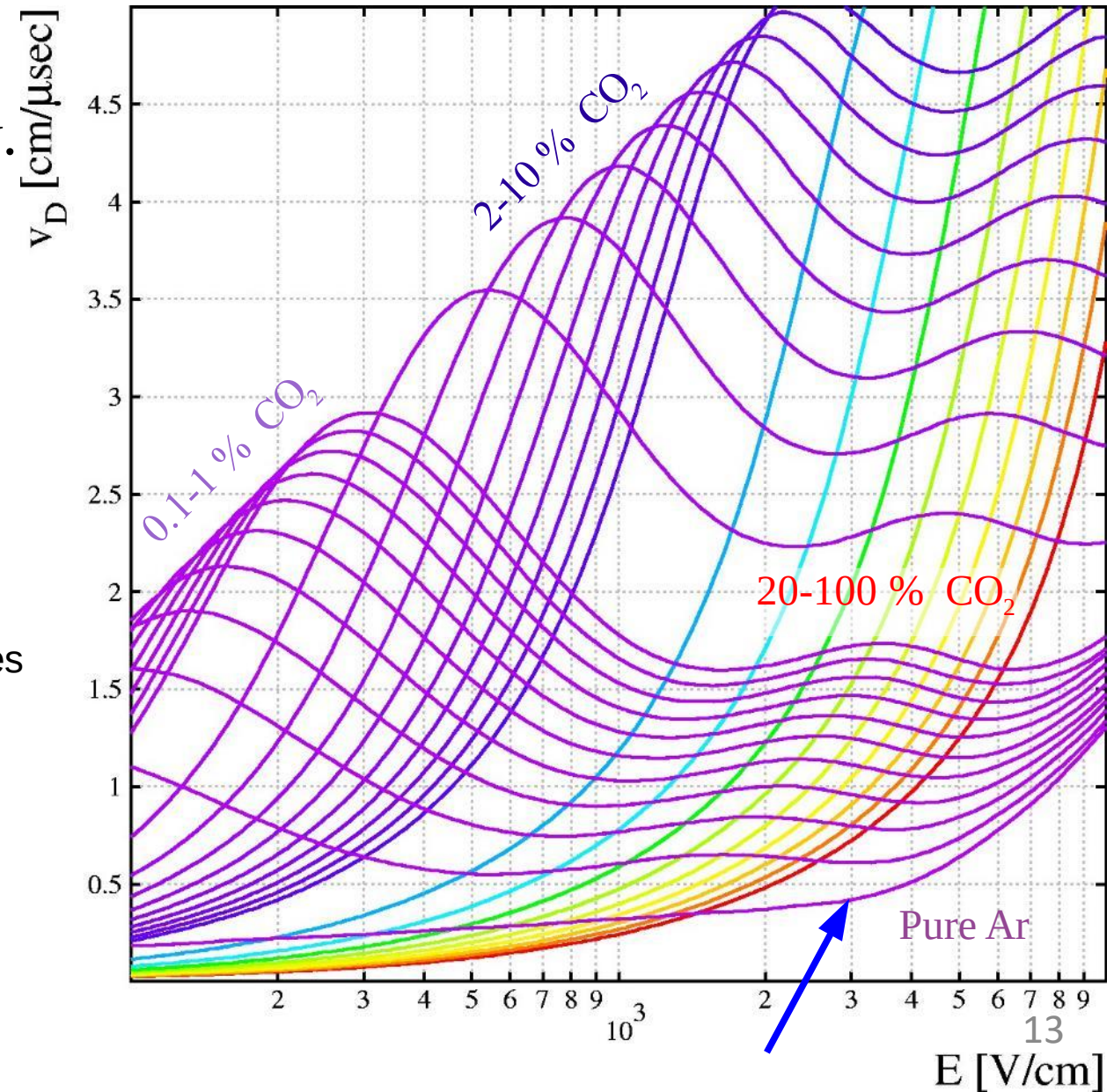


Adding CO₂

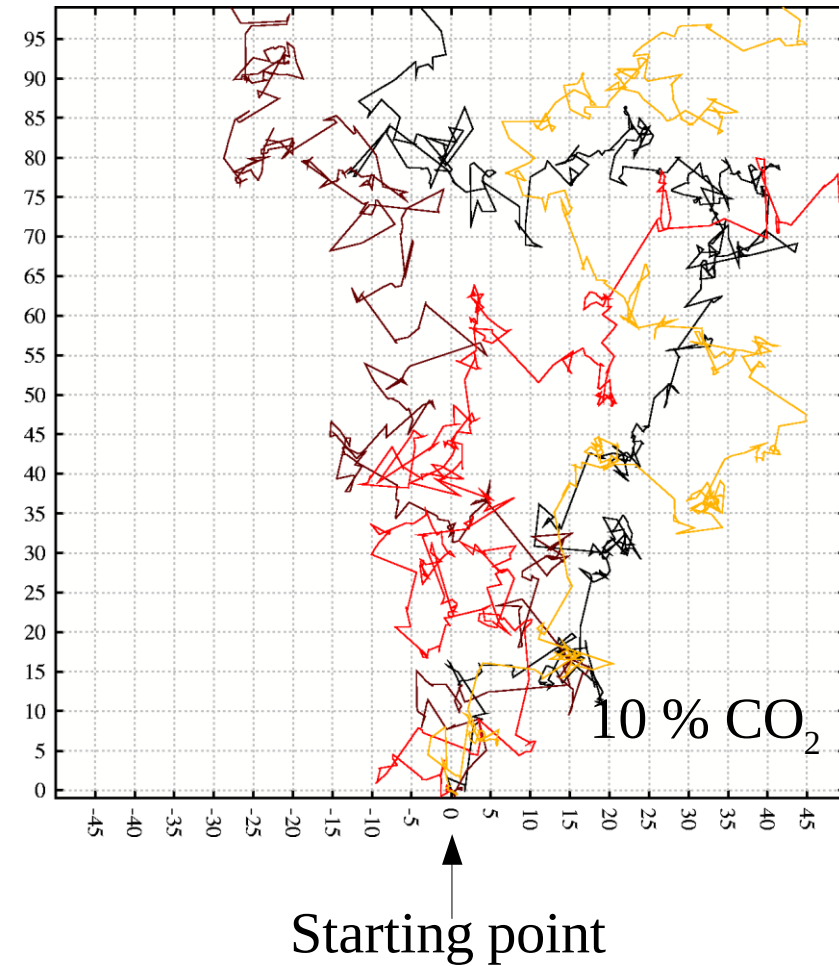
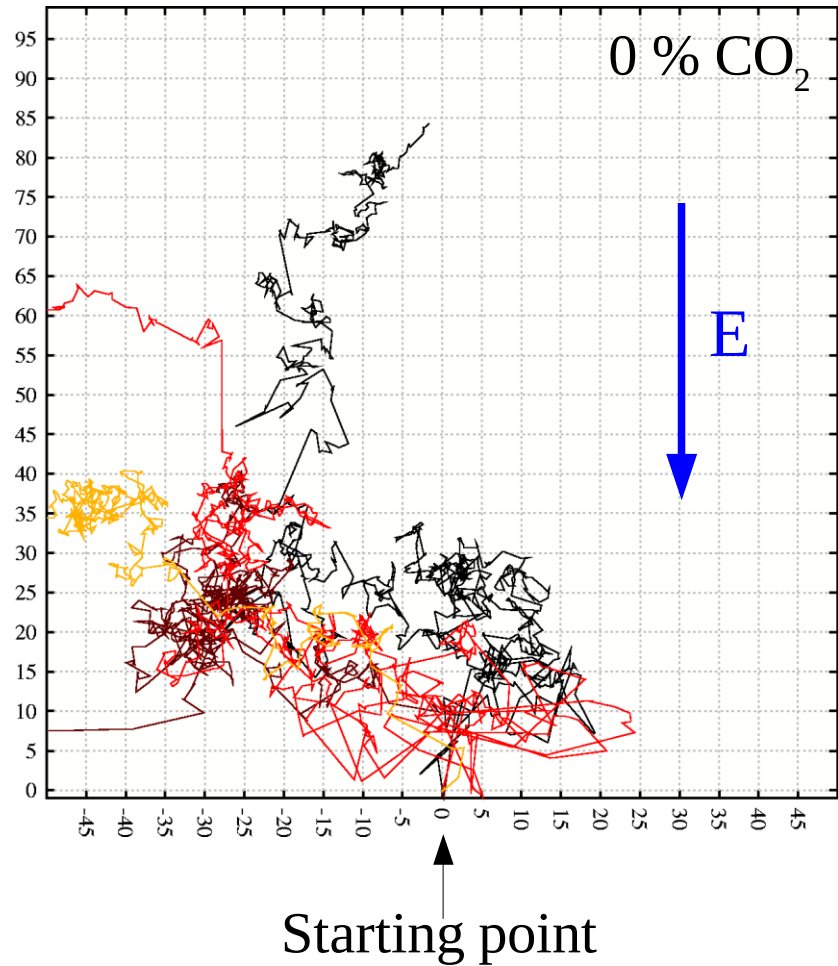
- ▶ CO₂ makes the gas faster, dramatically.
- ▶ Drift velocities calculated by Magboltz for Ar/CO₂ at 3 bar.

(Note where the [arrow](#) is !)

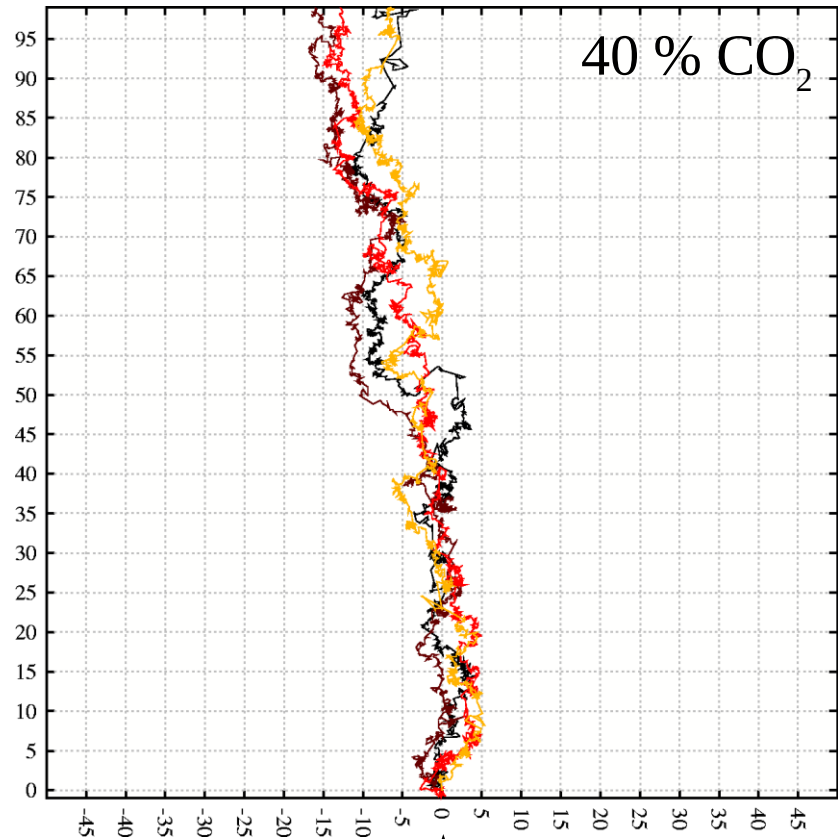
- We assume that the drift is in presence of an electric field constantly providing energy to the electrons
- This energy is accumulated in between collisions, and dissipated
- The electron energy distribution function is shaped by the dissipation provided by molecules rich of vibrational modes
- Depending on it the electron energy distribution is concentrated in a permitted band, in this case optimal to minimize the scattering with Ar molecules
- This «cooling effect» depends on the respective concentrations, on the dissipation cross-sections and on how the interaction cross section depends on the electron velocity.



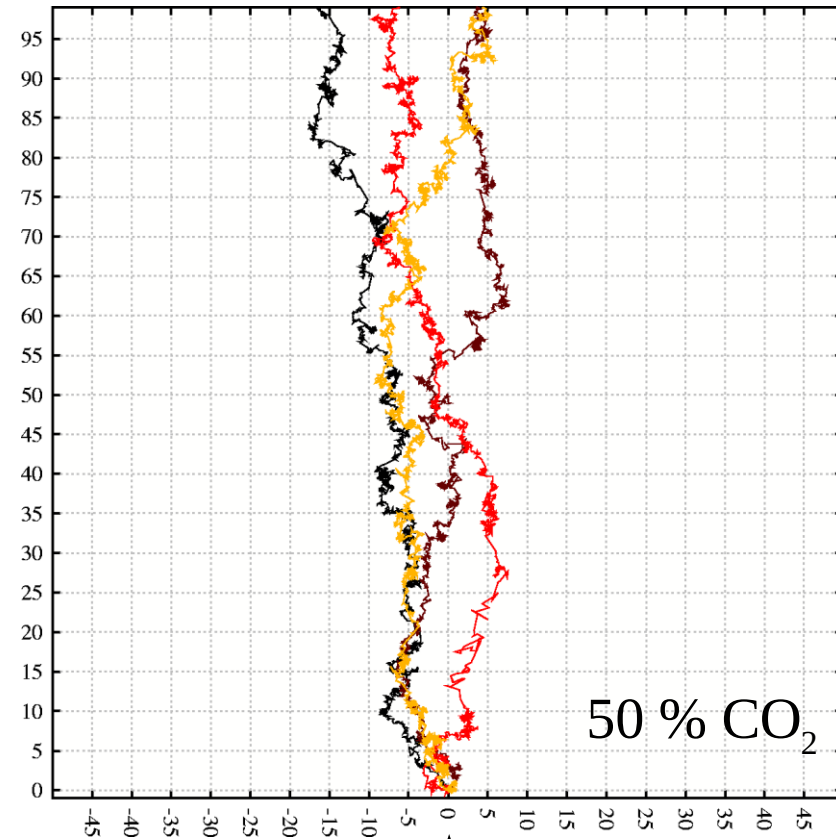
Electrons in Ar/CO₂ at $E=1$ kV/cm



Electrons in Ar/CO_2 at $E=1$ kV/cm



Starting point

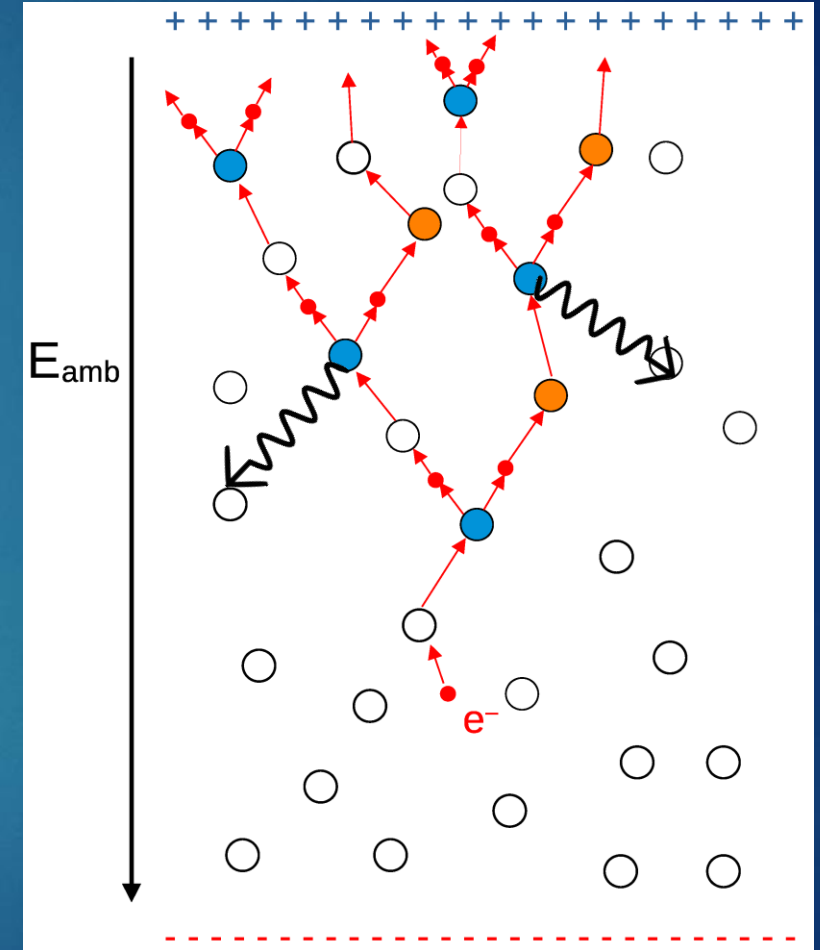


Starting point

Importance of mixtures

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- ▶ Gaseous detectors “secret” are the mixtures of gases, specifically tailored
- ▶ The previous example shows how different molecules can influence the drift velocity but there are many aspects influenced by the gas mixture components, often dependent on the electron energy distribution:
 - ▶ The Attachment: the capture cross section of electronegative components
 - ▶ The multiplication length: the distance between two consecutive ionizing collisions → depends on the trade-off between energy accumulation and dissipation
 - ▶ The photon quenching: the photon capture cross section. This last has not to do with electron velocity, but energetic photons produced by atom recombination, can ionize at distance from the generation point, seeding other clusters of secondary ionization



The case of ionization chamber

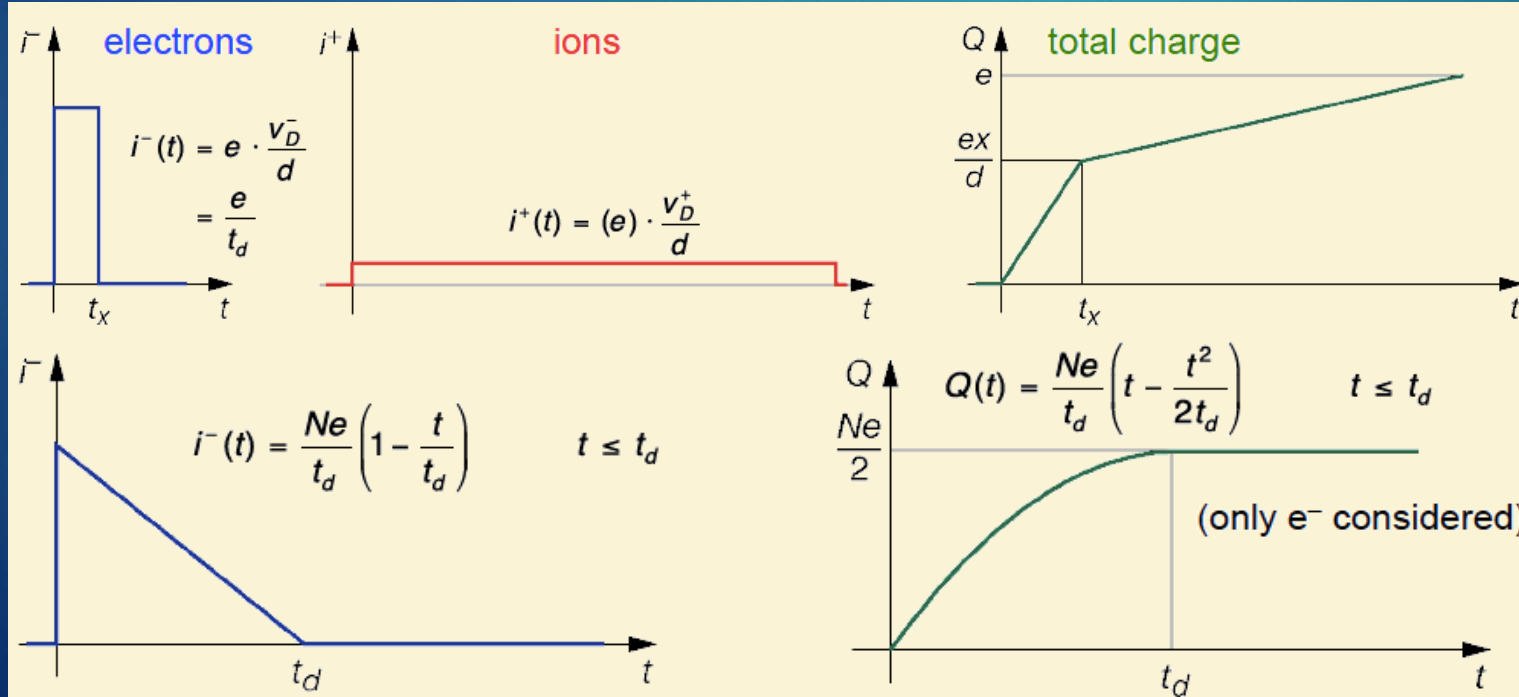
- An **ionization chamber** is operated at a voltage which allows full collection of charges, but below the threshold of amplification.
 - For a typical field strength 500V/cm and typical drift velocities the collection time
 - for 10 cm drift is about 2 μ s for e^- and 2 ms for the ions.
 - Ionization chambers are used in **nuclear industry** but rarely in particle physics (too low signal, too slow, not possible to measure single particles: $C_{\min} \approx 10^4 e \approx 1$ fC).

Shockley–Ramo theorem:

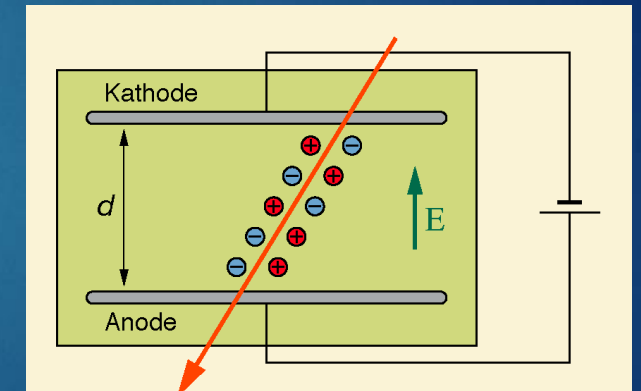
The instantaneous current i induced on a given electrode due to the motion of a charge is given by $i = E_v q v$

i is NOT given by the arrival of the electrons!

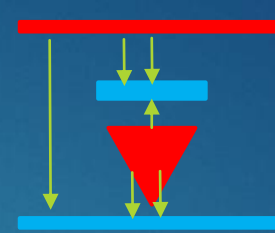
ICs however illustrate that the basic concepts to be applied also for the gaseous amplification



Planar ionization chambers,

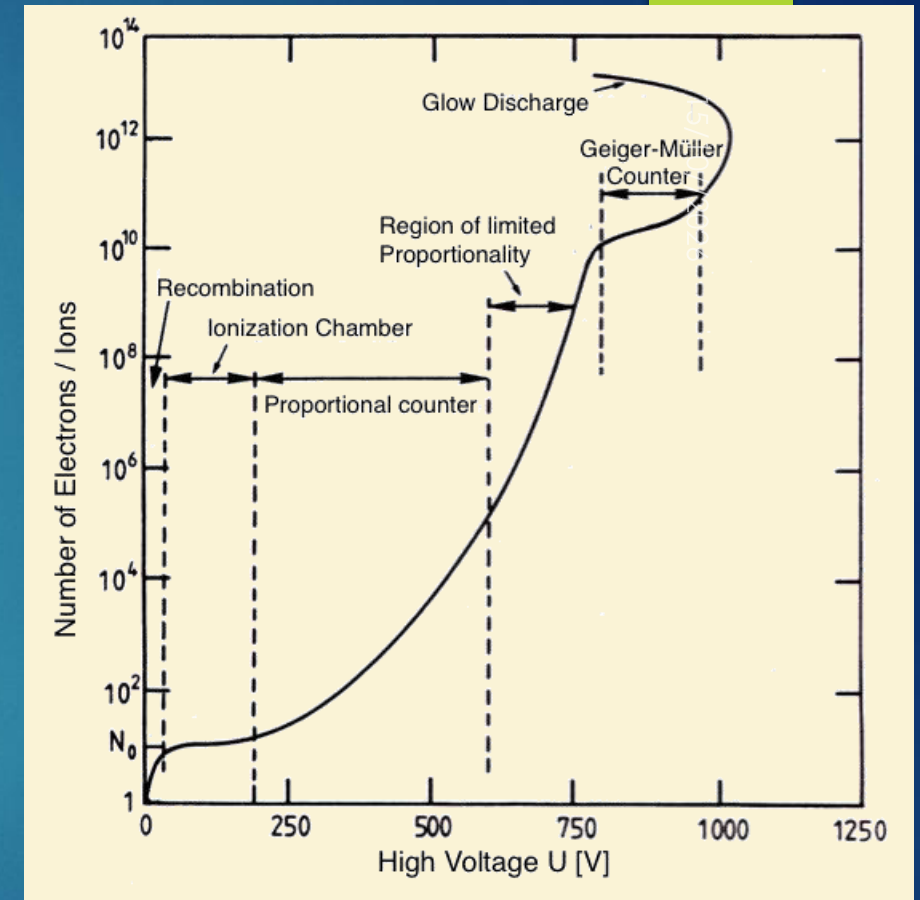


Discharge in gases



- The **gain G** is defined as the ratio of electrons delivered
 - at the anode N_A to the number of primary electrons N , $G=N_A/N$.
- $G < 1$: **Recombination**
 - most of the e/ion pairs recombine or get attached by an electronegative atom
- $G \approx 1$: **Ionisation chamber**
 - no amplification, only primary particles collected. Useful for dosimetry/flux meas.

- $G \approx 10^3 - 10^5$: **Proportional counter / proportional mode**
 - An **avalanche** develops which G is statistically constant and independent on the primary ionization
- $G \approx 10^5 - 10^8$: Region of **limited proportionality or saturated avalanche**
 - The electrons of the developing avalanche build up space charge limiting the effective field. The growth is not exponential i.e. electrons are not independent
- $G \gtrsim 10^8$: **Geiger** (or streamer) region
 - The signal is independent on the primary ionization. The detector counts.



*note: numbers only exemplary.
Strong dependence on gas and geometry*

- discharge operation**: triggered by a single e/ion pair, the electrodes connect by a streamer build up a self sustaining discharge triggered by extraction of electrons from the cathode, which is heated by the discharge itself

Avalanche multiplication

Large electric field yields
large kinetic energy of electrons ...

→ Avalanche formation

Larger mobility of electrons results in liquid
drop like avalanche with electrons near head ...

Mean free path: λ_{ion}
[for a secondary ionization]

Probability of an ionization per
unit path length: $\alpha = 1/\lambda_{\text{ion}}$ [1st Townsend coefficient]

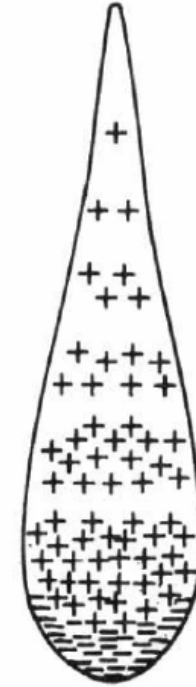
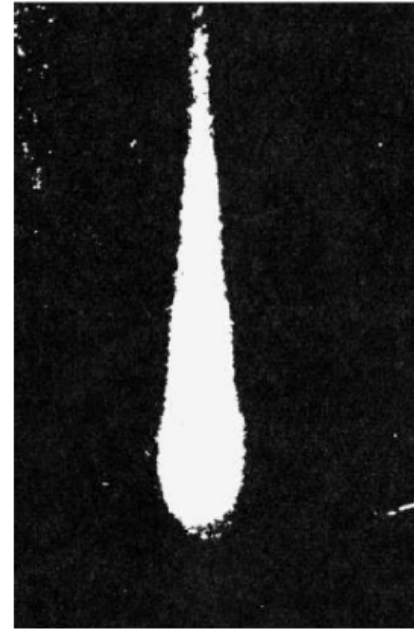
$$dn = n \cdot \alpha dx \quad n(x) = \text{electrons at location } x$$
$$n = n_0 e^{\alpha x}$$

Gain:

$$G = \frac{n}{n_0} = e^{\alpha x} \quad \text{and more general for } \alpha = \alpha(x): \quad G = \frac{n}{n_0} = \exp \left[\int_{x_1}^{x_2} \alpha(x) dx \right]$$

[Raether limit: $G \approx 10^8$; $\alpha x = 20$; then sparking sets in ...]

Townsend avalanche



Drop-like shape of an avalanche

Left: cloud chamber picture

Right: schematic view

The logistic saturated avalanche model

Resistive Plate Chamber avalanche

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- Primary ionization follow the Poisson distribution

$$f(k; \lambda) = \Pr(X=k) = \frac{\lambda^k e^{-\lambda}}{k!},$$

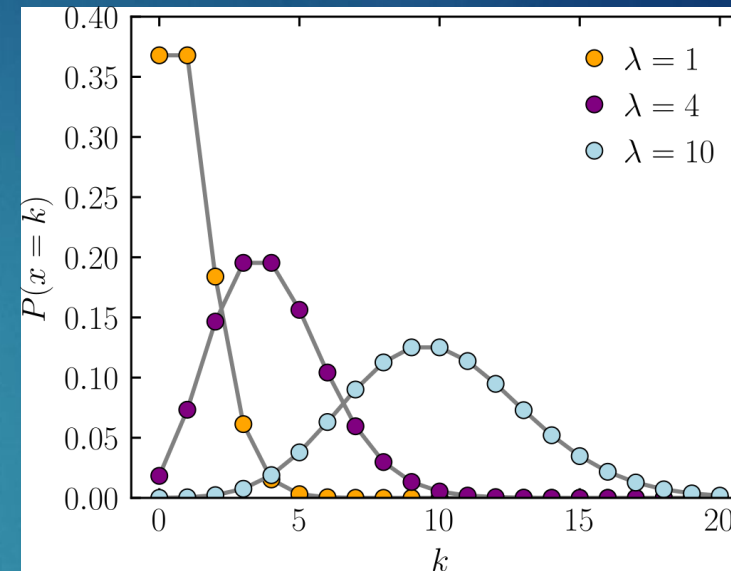
- Driven by the gas electron density
- The amount of energy released in each point follows a power law, typically for RPCs 70% of clusters has a single electron
- 1-P(0) should be the ma efficiency

- Proportional regime: $\alpha = 1/\lambda_{ion} = \text{constant}$

$$dn = n \cdot \alpha dx \Rightarrow n(x) = n_0 e^{\alpha x}$$

$$G = \frac{n(x)}{n_0} = e^{\alpha x}$$

- Valid for $G < 10^5$

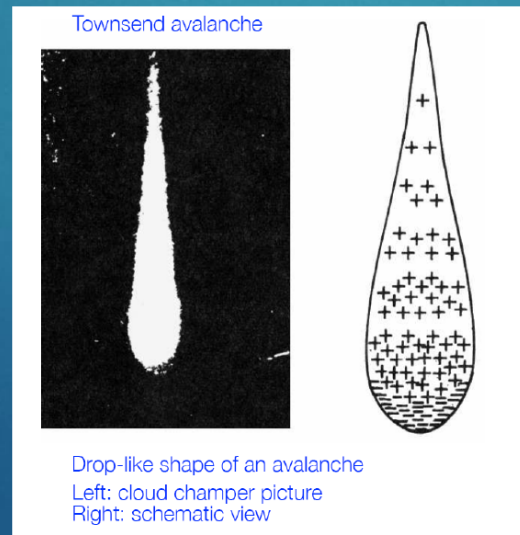


- Attachment: η is the probability that an electron is captured by an electronegative molecule and depends on the electric field as α

$$dn = n \cdot (\alpha - \eta) dx \Rightarrow n(x) = n_0 e^{(\alpha - \eta)x}$$

$$G = \frac{n(x)}{n_0} = e^{(\alpha - \eta)x}$$

- Due to the attachment, a fraction of the primary ions are captured before the avalanche can develop



Saturated Logistic Avalanche

- Townsend, Rather, Meek et. al developed a description of the avalanche growth in approximation of independent electrons
- This is very suitable for describing proportional detectors
- It fails in case of larger avalanches since electron field is relevant
- RPCs strong and uniform electric represents an ideal template for the study of this process

The experimentally observed growth of the avalanche charge recalls the Logistic function introduced firstly in 1845 by Verhulst [8] to describe the growth of a biological population, that tend to become stationary in presence of a limited flow of food resources due to the fact that the number of individuals able to reproduce become constant.

In our case the experimental data on the total charge can be compared with the integral of the logistic function, accounting for the total population: the multiplying (active) electrons and the spectator electrons

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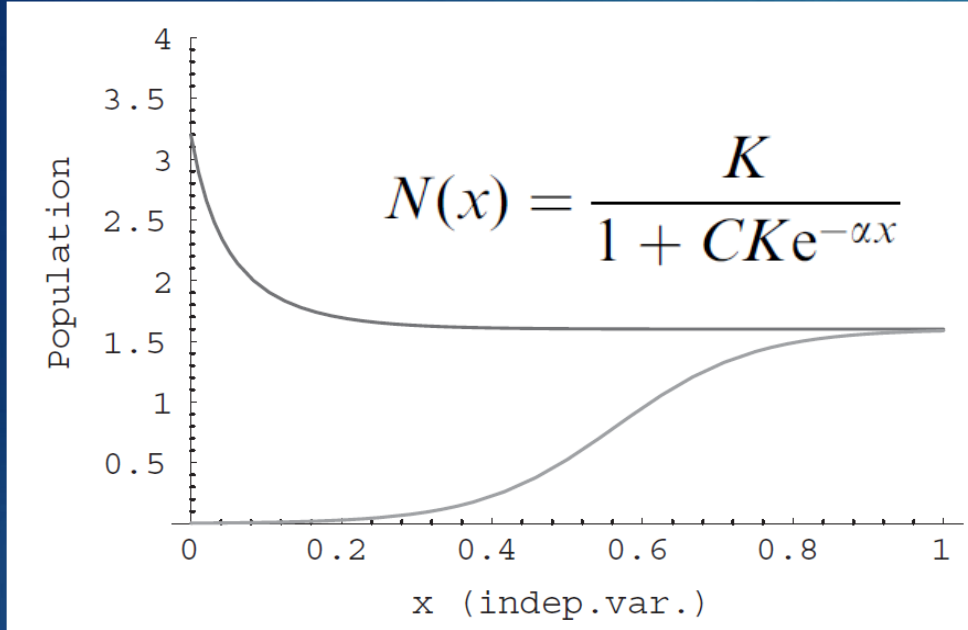
The logistic avalanche model

- The Logistic equation is obtained by the lowest order non-linear correction to the usual exponential growth equation (equivalent to the Townsend theory)

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- $\frac{dN}{dx} = \alpha N - \beta N^2$ $\frac{dN}{dx} = \alpha N \left(1 - \frac{N}{K}\right)$ $K = \frac{\alpha}{\beta}$ In each other, in the Logistic avalanche case N electrons interact with themselves linearly $\rightarrow$ proportionally to N^2
- α and β mean the rate at which the free electrons are created and lost from the active avalanche front.
- The free running variable x in represents system evolution parameters such as the applied field or the avalanche path.
- the growth rate tends to zero as N reaches K
- For $\beta = 0$ the equations is the classic one

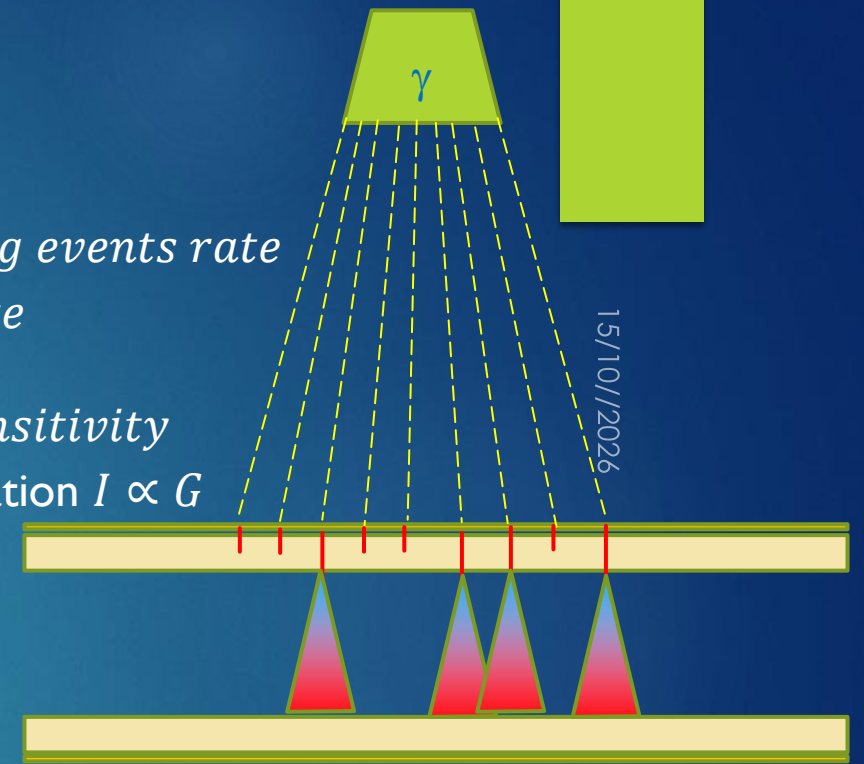
The logistic avalanche model



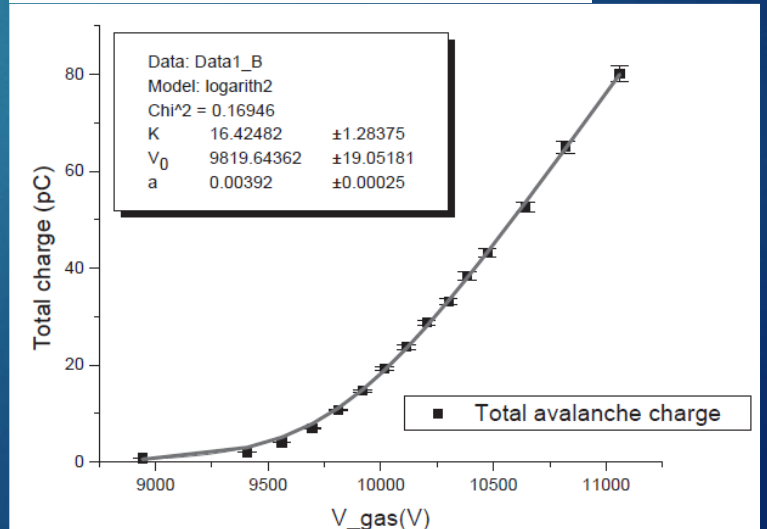
- It describes Q_{act} , the ‘active’ avalanche, responsible for the creation of further ionization.
- Q_{act} is a fraction of Q_{tot} the total amount of free electrons
- x and V are conjugated variables
 - Increasing the avalanche length at fixed field

$\Updownarrow$
 - Increasing $\alpha(V)$ at fixed gap

- Average G (gain)
= Current/ionizing events rate
- Ionizing events rate
= source intensity
* solid angle * sensitivity
- For a constant irradiation $I \propto G$



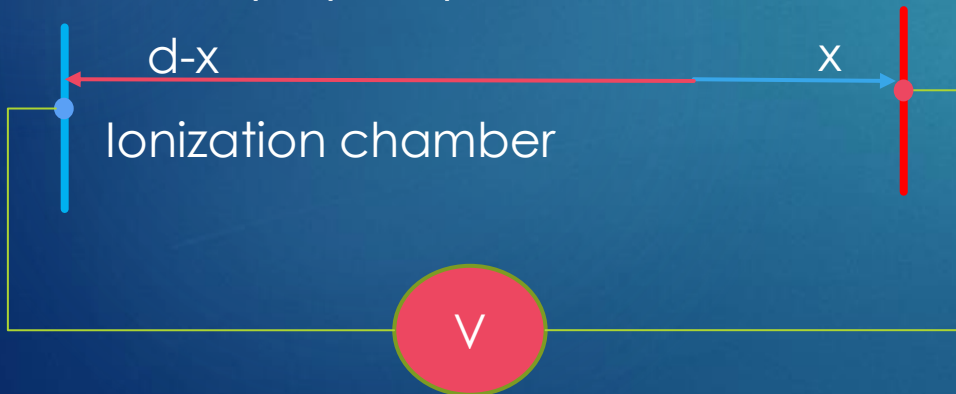
$$Q(V) = K \ln(1 + e^{a(V-V_0)})$$



Signal induction: $Q_{\text{tot}}/Q_{\text{prompt}}$ ratio

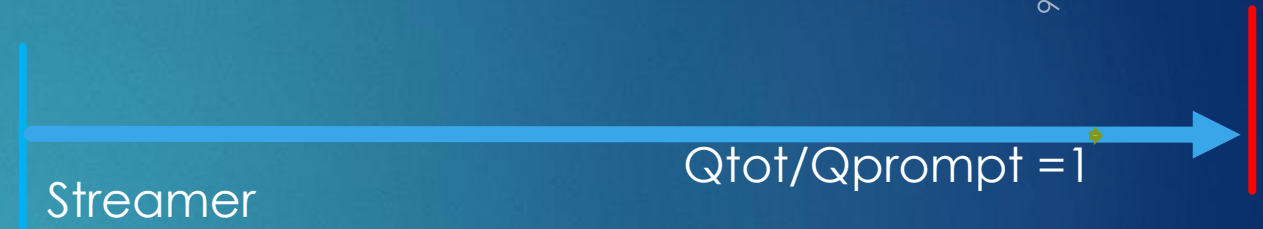
Q_{tot} is the “price” to pay in charge to deliver a signal Q_{prompt} (the charge induced by the moving electrons)

- Simplest case, the ionization chamber: no multiplication
- When an electron and the ion reach the respective electrodes, a charge $Q=1e$ has been induced in the circuit
 - electron path = $x \rightarrow$
 - $Q_{\text{prompt}} \propto x/d$
 - $R_q = Q_{\text{prompt}}/Q_{\text{tot}} \propto x$

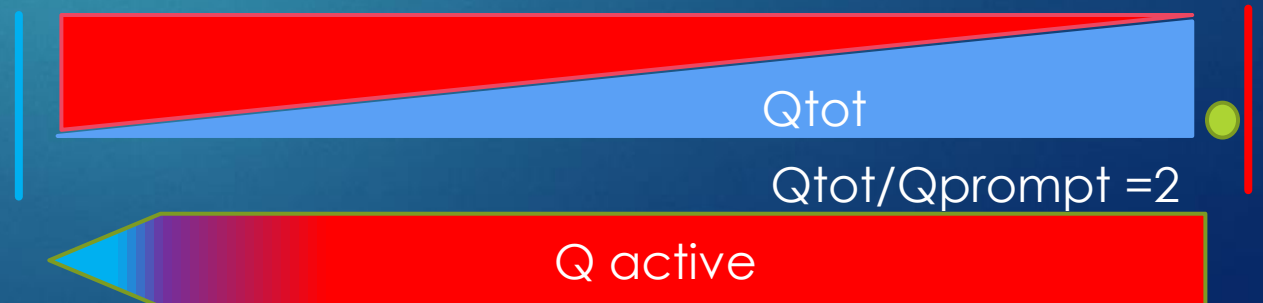


SPECIAL CASES

Streamer: a conductive filament of plasma connecting anode to cathode $\rightarrow$ electron path = $d \rightarrow R_q = 1$



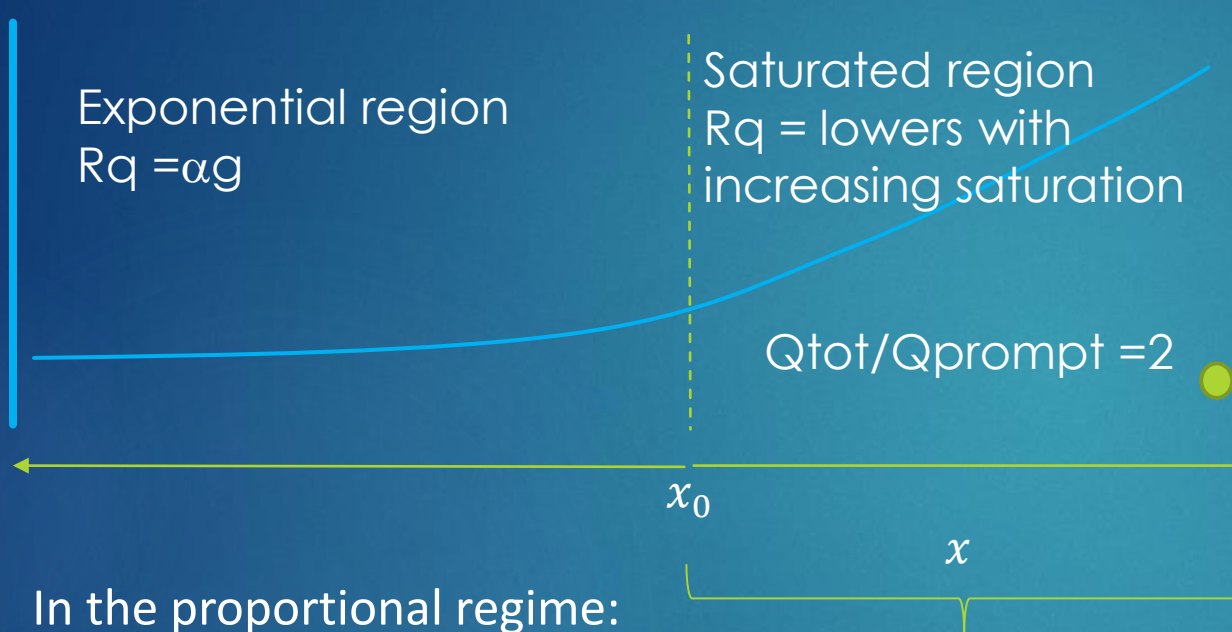
- For the saturated avalanche, R_q depends on the field,
- And will decrease from αg to 2 (extreme case)
- Extreme saturation: $Q_{\text{act}} = K$ at the cathode $\rightarrow Q_{\text{prompt}}$ increases linearly along $x \rightarrow Q_{\text{tot}} = 2 * Q_{\text{prompt}}$



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The Q_{tot} to Q_{prompt} ratio

$$R_Q = Q_{tot}/Q_{prompt}$$

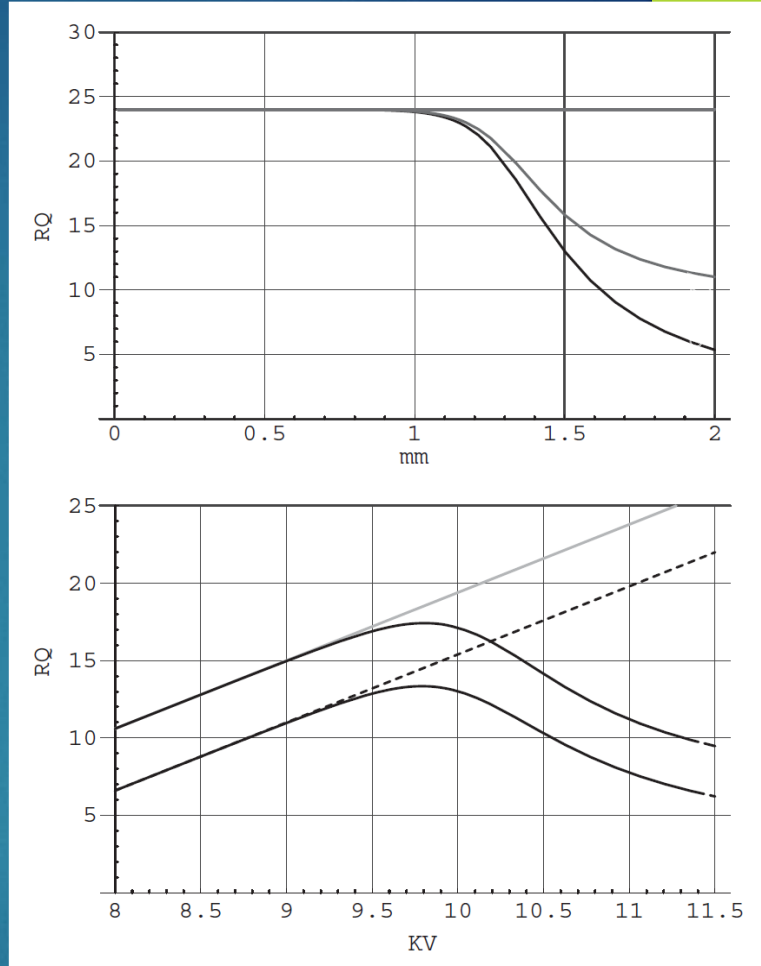


$$Q_{tot}(x) \cong \int_0^g n_0 e^{\alpha x} = n_0 \alpha g \cdot e^{\alpha x}$$

Example: $G = 5 \cdot 10^4 \Rightarrow \alpha g \cong 11$

$G = 5 \cdot 10^6 \Rightarrow \alpha g \cong 15$ proportional mode limit

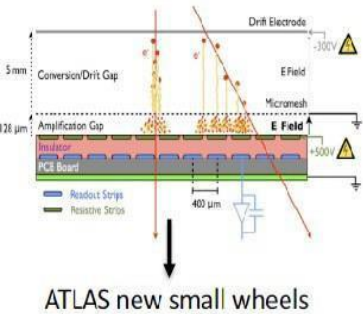
$G = 5 \cdot 10^8 \Rightarrow \alpha g \cong 20$ Meek limit



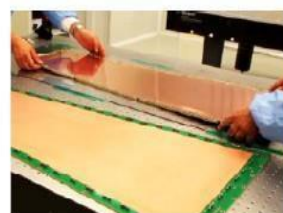
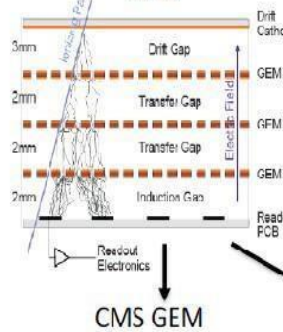
For a completely saturated avalanche, i.e. $x \gg x_0$ yields $Q_{tot}(x) \cong K \propto x$ and R_Q is found to decrease down to the limit value 2

Comparison of the main gaseous detector families

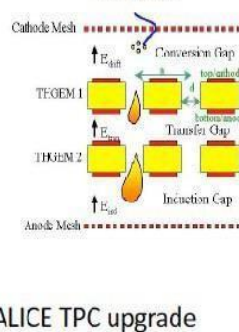
MicroMegas (MM)



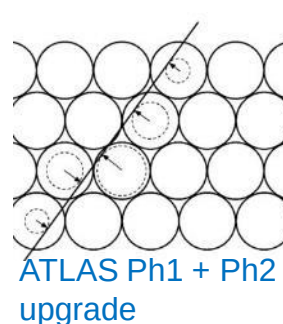
GEM



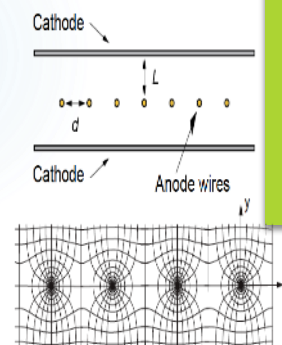
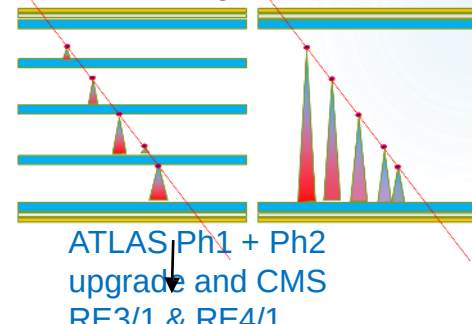
THGEM



sMDT



RPC



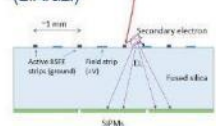
28



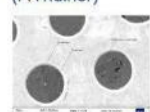
Muon detector technologies

AND NEW IDEAS

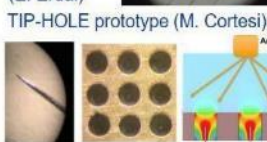
Positive Ion Detection in gaseous TPC (L. Arazi)



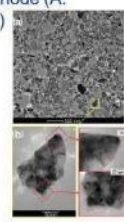
Charge transfer properties through graphene (P. Thuiner)



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



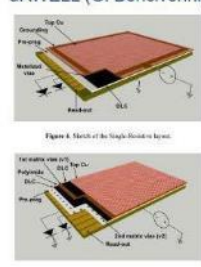
Nanodiamond photocathode (A. Valentini)



3D printed THGEM (F. Brunbauer)



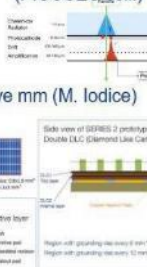
uRWELL (G. Bencivenni)



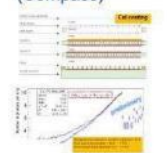
Scream mm (M. Chefdeville)



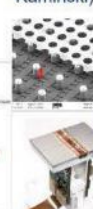
PICOSEC mm (PICOSEC coll.)



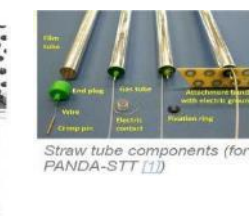
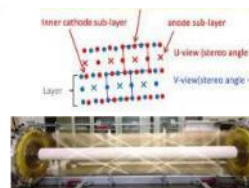
COMPASS RICH-1 (Compass)



GridPix (J. Kaminski)



Small pad resistive mm (M. Iodice)

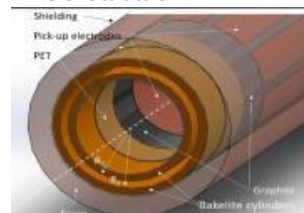


sRPC (Bencivenni)

single gap semi-conductor R. Cardarelli



RCC Cardarelli

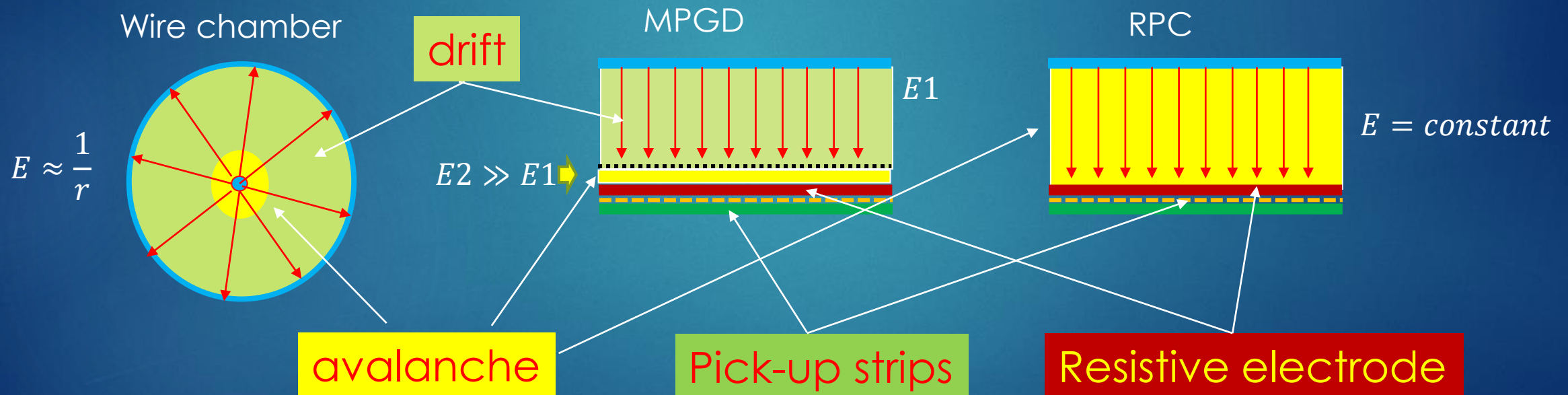


Basic principles of gaseous detectors

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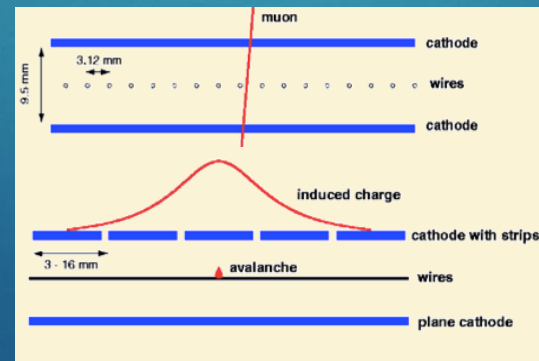
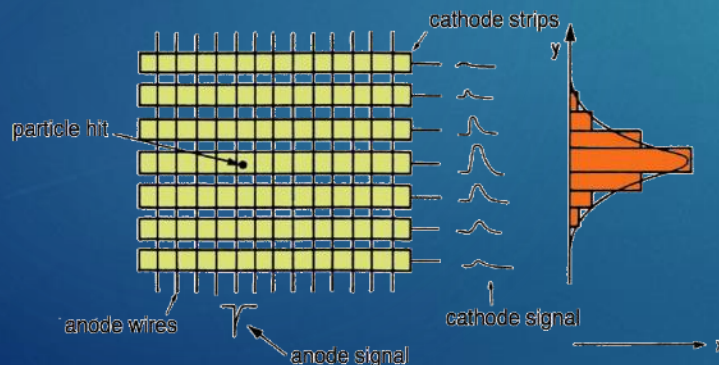
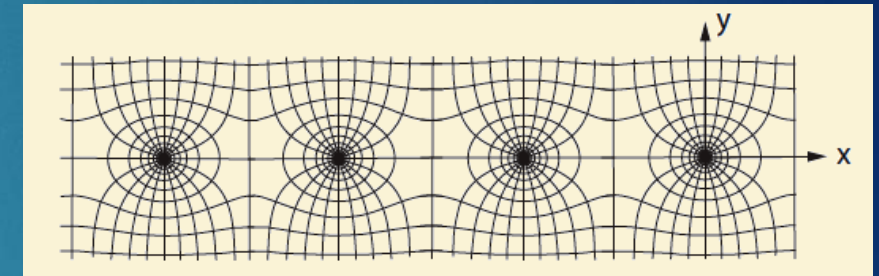
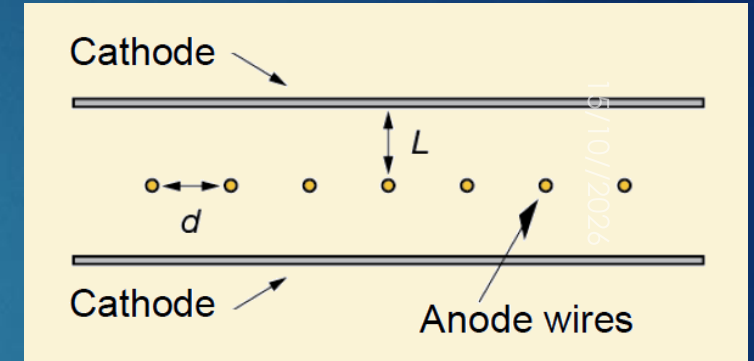
15/10/2026

- ▶ All gaseous detectors designed for muons share the same base principle:
 - ▶ A gaseous target thick enough for a MIP to release a sufficient primary ionization
 - ▶ An electric field sufficiently strong to start an avalanche multiplication
 - ▶ A segmented pick-up electrode to readout the signal and extract a space-time information

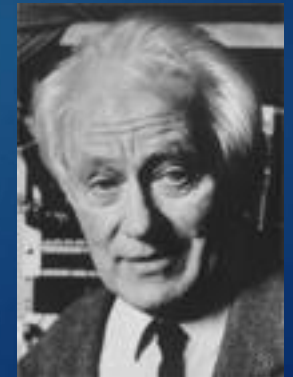


Multi wire proportional chamber

- A repetitive pattern of Geiger tubes without walls...
- Narrow wires allow a higher rate capability (typically 10 kHz/cm²)
- Typical gas amplification in MWPC is 10⁵
- Space in between wires is 1-5 mm and sets the space resolution
 - By using the wire position: $\sigma_x \approx d/\sqrt{12} \approx 500 \mu\text{m}$
 - Using also the charge centroid: 50 μm achievable.
- A variant of the MWPC to improve the space resolution is the Cathode strip chamber

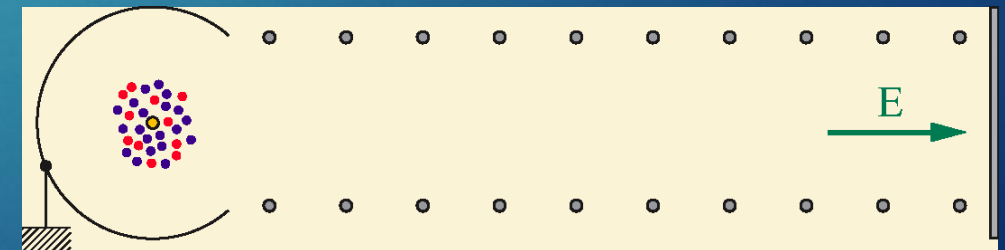
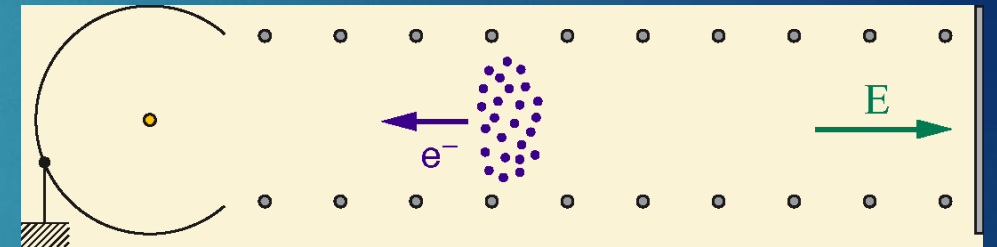
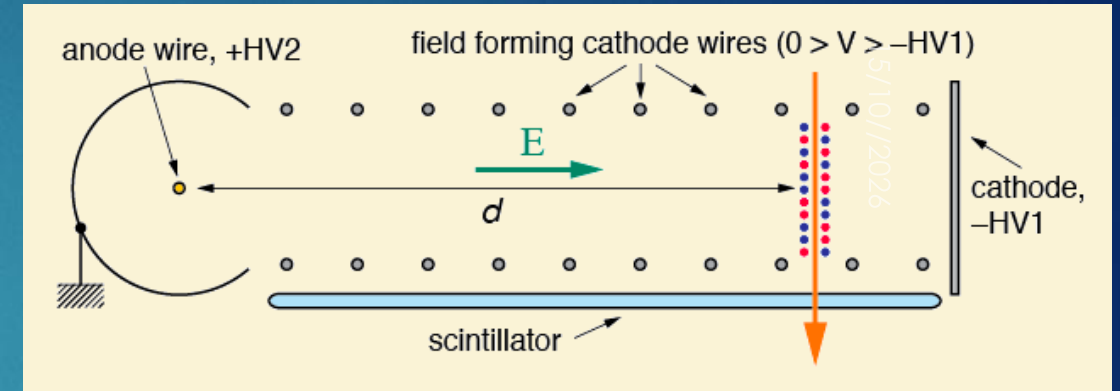


MWPC was the first electronic detector (1968)!
Georges Charpak (1924-2010)
Nobel prize 1992

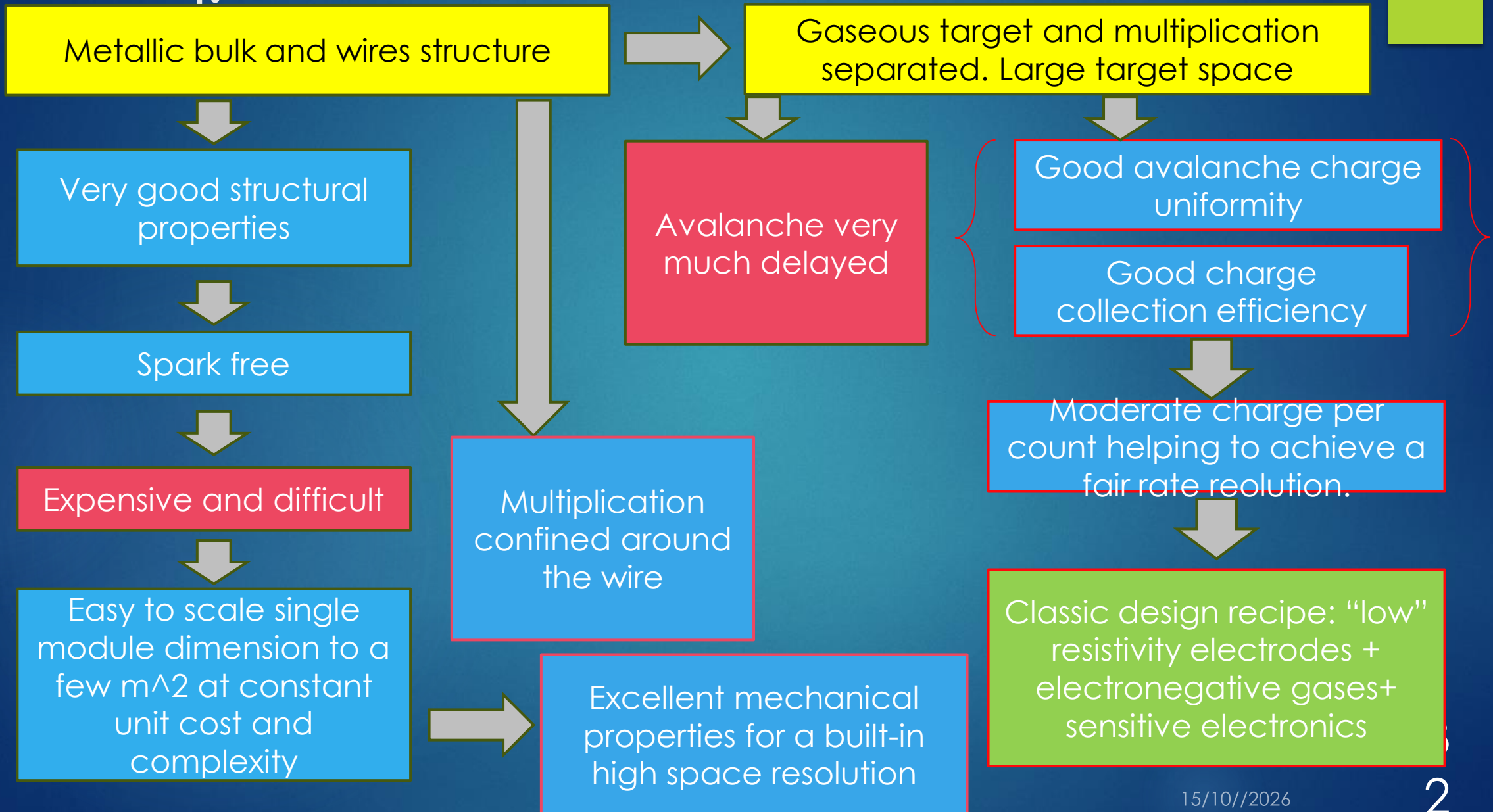


Drift chambers

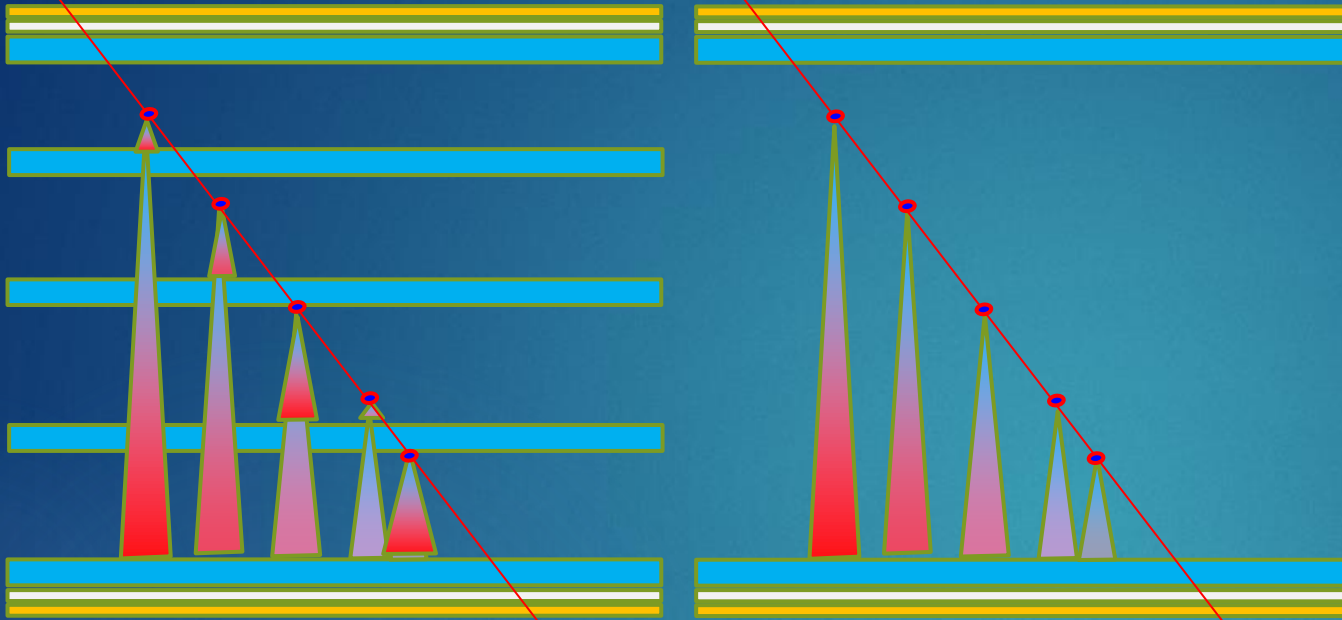
- Operating principle:
 - Take into account **e^- drift time** and **separate drift** and **amplification**
- Charged particle traversing the chamber produce ionization.
 - Need to be supplemented with e.g. an scintillator signal that starts a timer ($t = t_0$), or other subdetector components provide a trigger.
- Electrons drift to the anode wire.
- Electrons reaching the wire create secondary ionization (avalanche) and trigger a signal ($t = t_1$).
- From the **time difference** the **distance** of the traversing particle **to the wire** is deduced:
 - $\Delta t = t_1 - t_0, x = v \cdot \Delta t$



MWPC Strength vs. weakness



Resistive Plate chambers at a glance



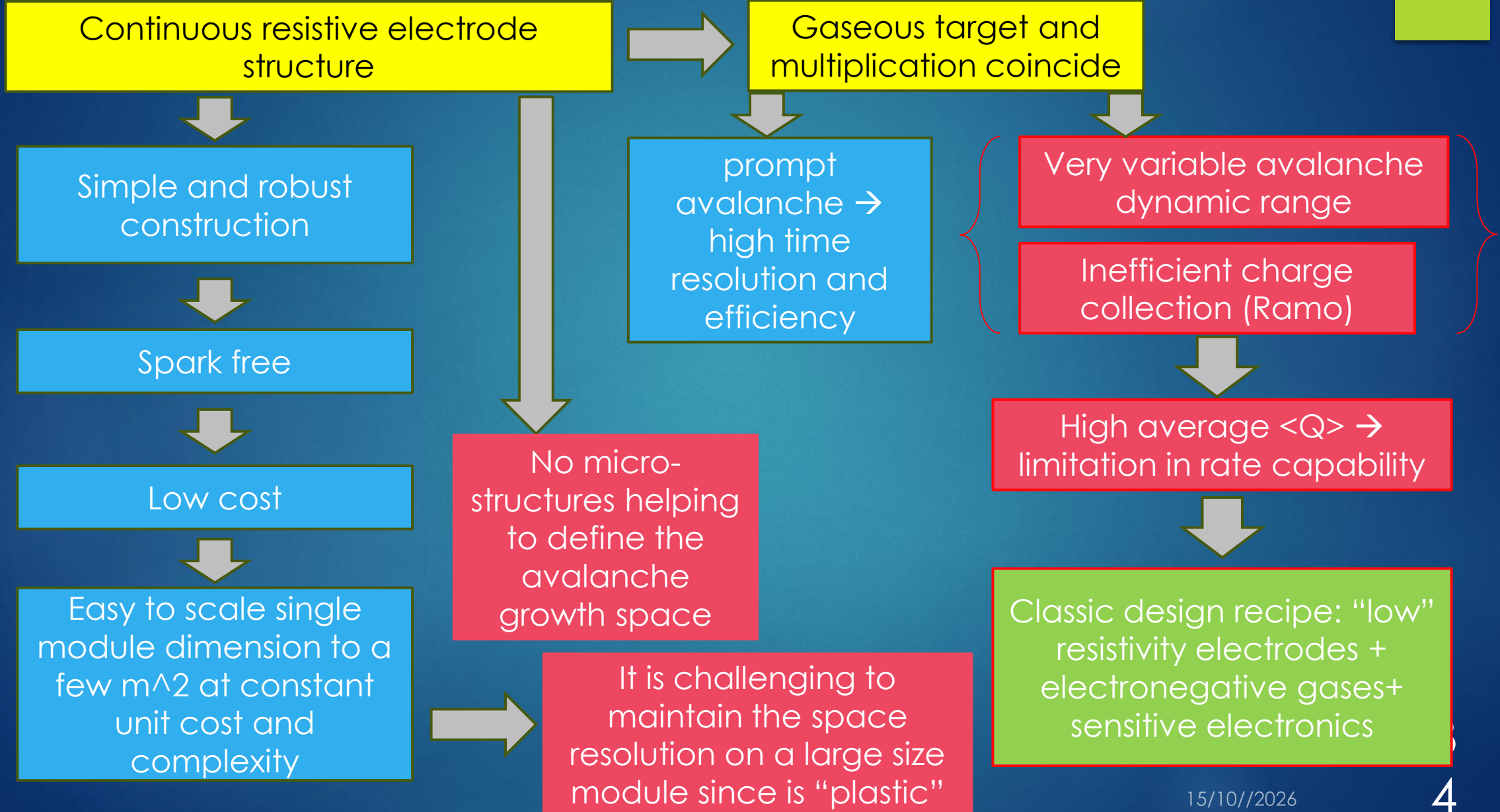
Common features

- ▶ high ρ electrodes $\rightarrow$ Spark less
- ▶ Uniform electrode $\rightarrow$ simple
- ▶ uniform field $\rightarrow$ prompt signal
- ▶ Target and multiplication gap coincide $\rightarrow$ low latency
- ▶ Working at atm. Pressure
- ▶ Up to 0.1mm 2D localization
- ▶ Gas mixture

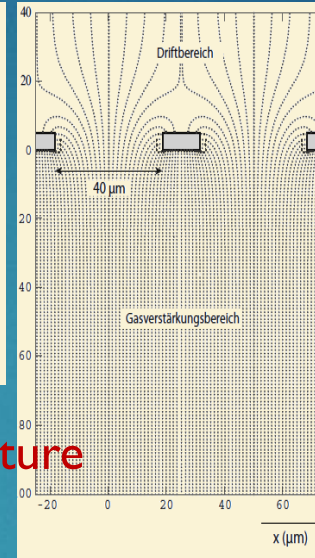
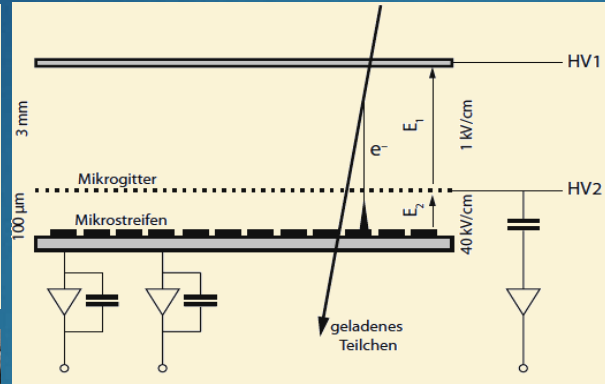
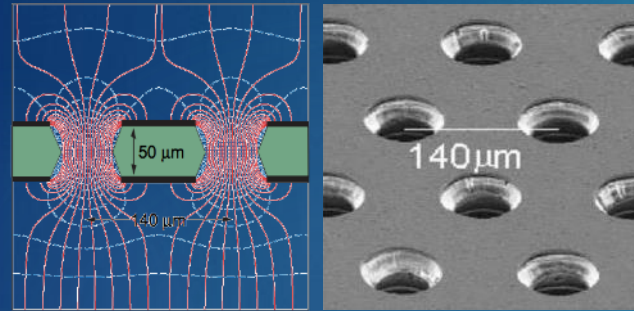
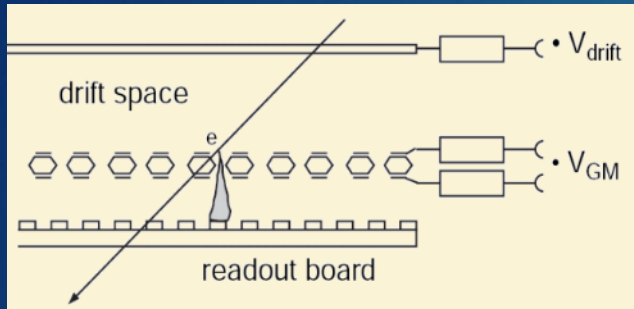
Feature RPC vs MRPC

- # OF GAPS $\rightarrow$ 1-2 – 4 TO TENS
- GAP SIZE $\rightarrow$ $\sim 1\text{MM}$ – $\sim 0.1\text{MM}$
- $\rho(\Omega\text{CM}) \rightarrow 5 \times 10^{10}$ – 5×10^{12}
- MODULE SIZE $\rightarrow 2\text{M}^2$ – 0.1M^2
- $\text{Hz/CM}^2 \rightarrow 10^4$ – 5×10^2
- $\sigma_t \rightarrow 300\text{PS}$ – 50PS
- ELECTRODE HPL – GLASS
- GAS R134A+ SF6 MIX

RPC Strength vs. weakness diagram



GEM and Micromegas at a glance



Common features

- ▶ Resistive layers → Spark safe
- ▶ micropattern → industry
- ▶ Target and amplification separated → small $\langle Q \rangle$
- ▶ Working at atm. Pressure
- ▶ 0.1 mm 2D localization
- ▶ Works with simple gases

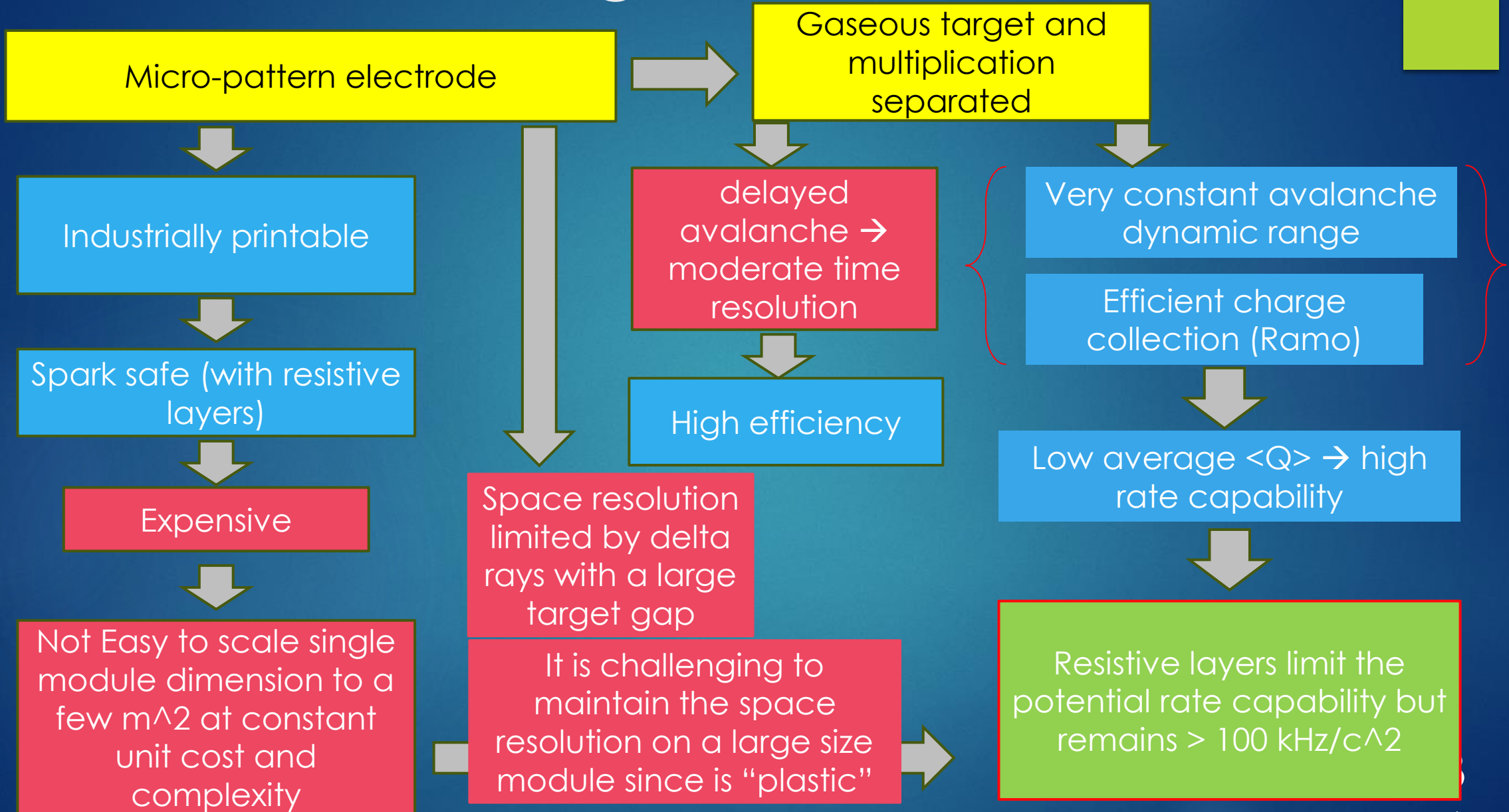
Micro Mesh Gaseous structure (Micromegas)

- Separate ionization region (6mm) from amplification region (100 μm)
- Fast signal: Collect **electrons** within 10 ns
- 100 μm spatial resolution achievable

Feature GEM vs MMGAS

- # OF GAPS → $> 3 - 1$
- GAP SIZE → $\sim$ A FEW MM TARGET + 0.05 MM MULTIPLICATION
- ρ (M Ω /SQUARE) → 100
- MODULE SIZE → 0.1 m² – 0.5 m²
- Hz/CM² → $10^5 - 10^5$
- σ_t → 10 ns – 10 ns
- ELECTRODE PCB – MESH
- GAS AR + CO₂ + IC₄H₁₀

MPGD Strength vs. weakness



Performance

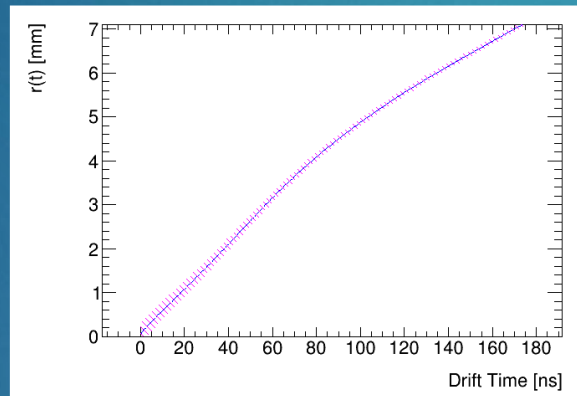
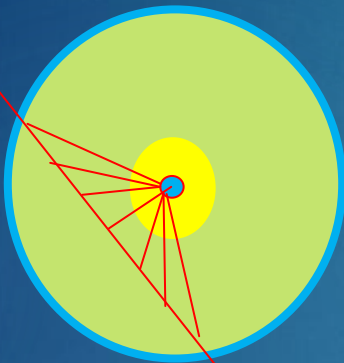
Space resolution principles

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- ▶ Space resolution is driven by 2 factors
 - ▶ Intrinsic localization of the event
 - ▶ Precision of the chamber geometry

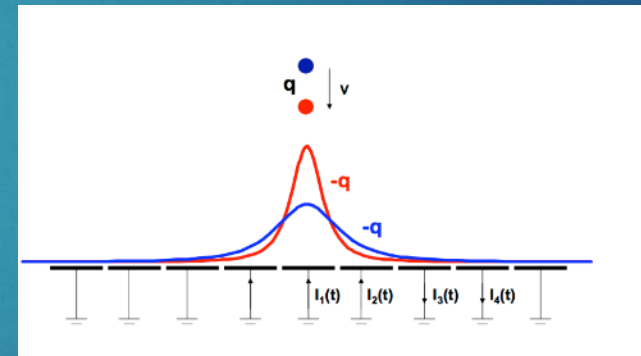
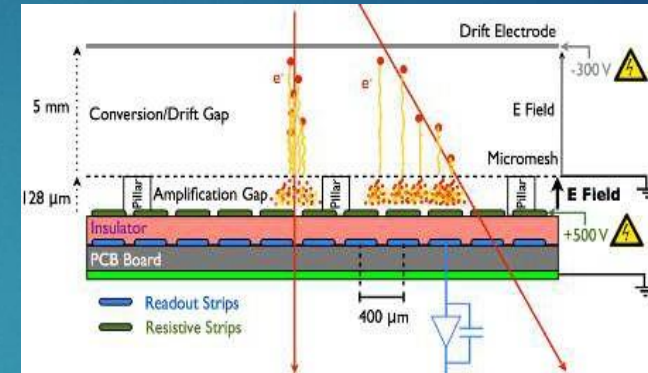
Wire chamber

$$E \approx \frac{1}{r}$$



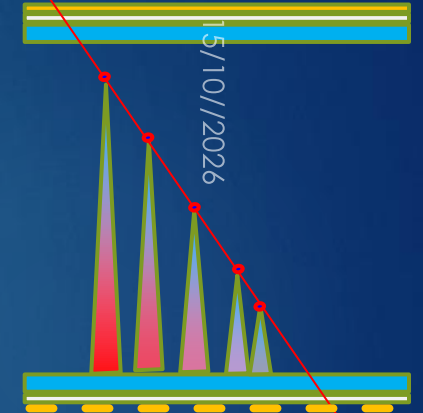
- ▶ Tubes and MWPC exploit the R-t relation of the ions drifting in the gas and rely on their metallic bulks which can be easily machined to offer a precise reference frame. Can obtain high precision with low channel density

MPGD



- ▶ RPCs and MPGD exploit electrostatic induction of the moving charges to calculate the charge centroid. The resolution is driven by the readout system segmentation and mechanical precision preserving it on large multi-layer chambers made of composite materials. Can obtain high precision with high channel density

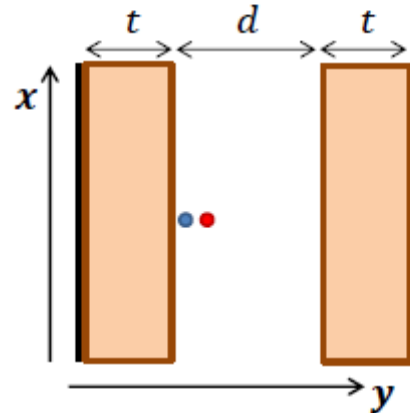
RPCs



The Physics model

An induced charge distribution model

The main limitation of this model is that it does not take into account the presence of the resistive electrodes. It also neglects the presence of other parameters, as graphite painting.



Considering the presence of the electrodes, the parameter δ can be written as

$$\delta \cong \frac{d + 2t}{\pi}$$

*C. Lu, Princeton University, Princeton, NJ 08544, USA
SNIC Symposium, Stanford, California – 3-6 April 2006

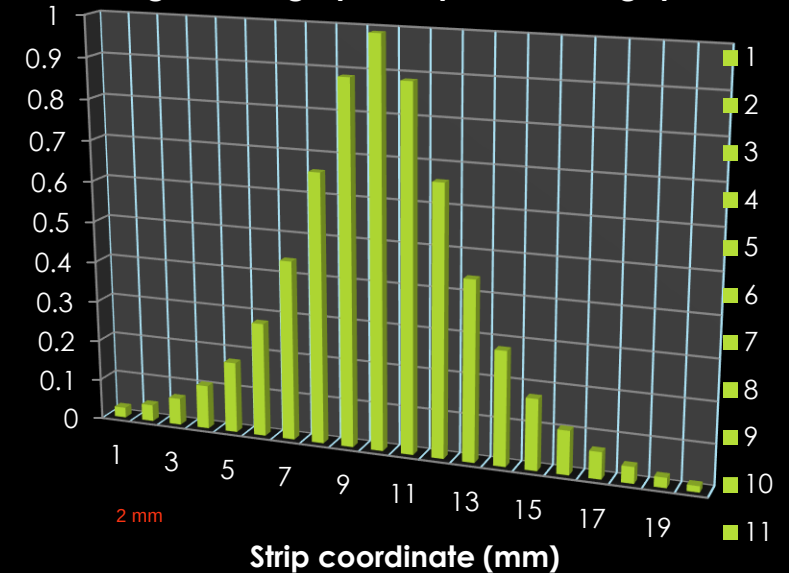
For simplicity, when the thickness of the electrode is similar to the gas gap and smaller than the strip pitch, the effect of the charge displacement with respect to the middle of the gap is negligible. This offers the possibility to use the model.

$$\sigma = \frac{q_{ind}}{2\pi\delta} \frac{1}{\cosh\left(\frac{x - x_0}{\delta}\right)}, \quad \delta \cong \frac{d + 2t}{\pi}, \quad q_{ind} = q \frac{\Delta y_{el}}{d + \frac{2 \cdot t}{\epsilon_r}}$$

L. Paolozzi, RPC2014 - Beijing

4

Integral charge per strip for a RPC gap



$$\sigma(x, \bar{x}) = \frac{A}{\cosh[(x - \bar{x})/\delta]}$$

$\Rightarrow$ integratin g over each strip

$$Q_i = \int_{x1}^{x2} \frac{A}{\cosh[(x - \bar{x})/\delta]} =$$

$$= A\delta \cdot \arctg\left[\left(e^{(x-\bar{x})/\delta}\right)\right]_{x1}^{x2}$$

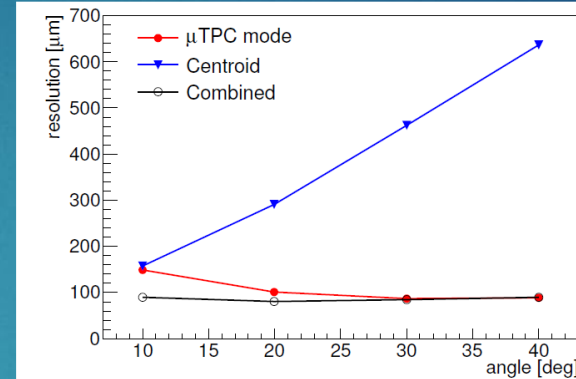
Space resolution performance

40

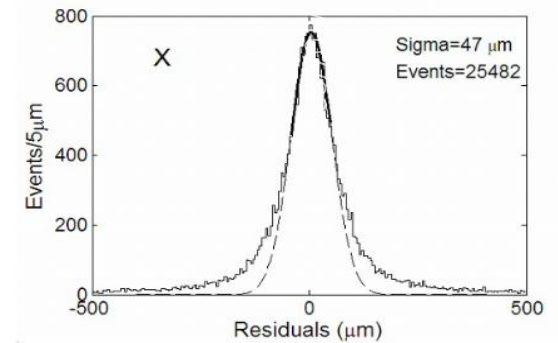
RPCs and MPGDs

- ▶ ATLAS MMGAS
 - ▶ resolution $\sim 100\mu\text{m}$ with 0.4 mm strips
- ▶ The drift gap is large $\rightarrow$ impact angle worsen resolution corrections needed (micro-TCP method)
- ▶ Affected by the B field
- ▶ A lot of care needed in construction
- ▶ Proof of principle on a small MRPC
 - ▶ resolution $\sim 50\mu\text{m}$ with 4 mm strips
 - ▶ RPC less sensitive to the angle $\rightarrow$ smaller gas gaps and a single dominant cluster
- ▶ 1m² 1mm gas gap ATLAS prototype reaching 1mm space resolution with 2.7cm strip pitch! Up to 10 kHz/cm² at GIF++
- ▶ Space resolution is not a classic RPCs performance, though physics is not preventing it...

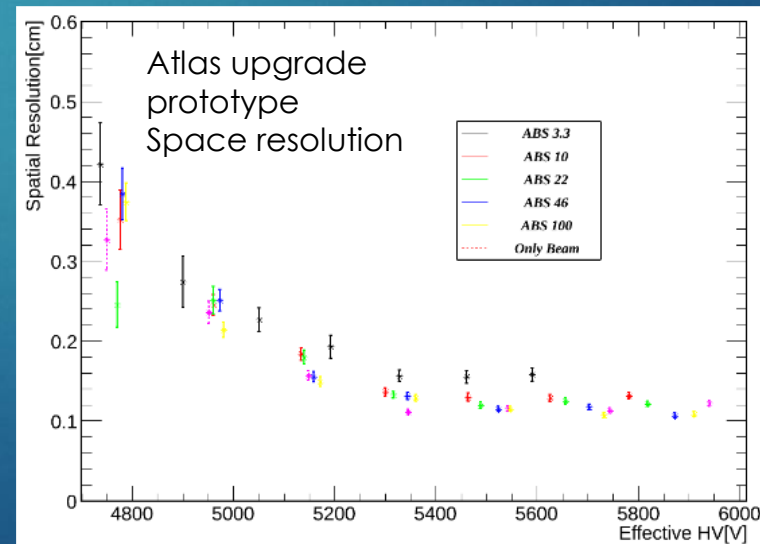
MMGAS



MRPC



Planar technologies need further R&D for a simple and reliable structures to emulate DTs

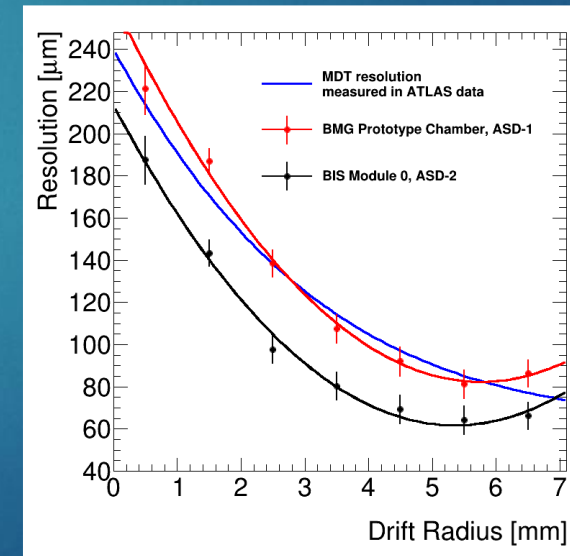
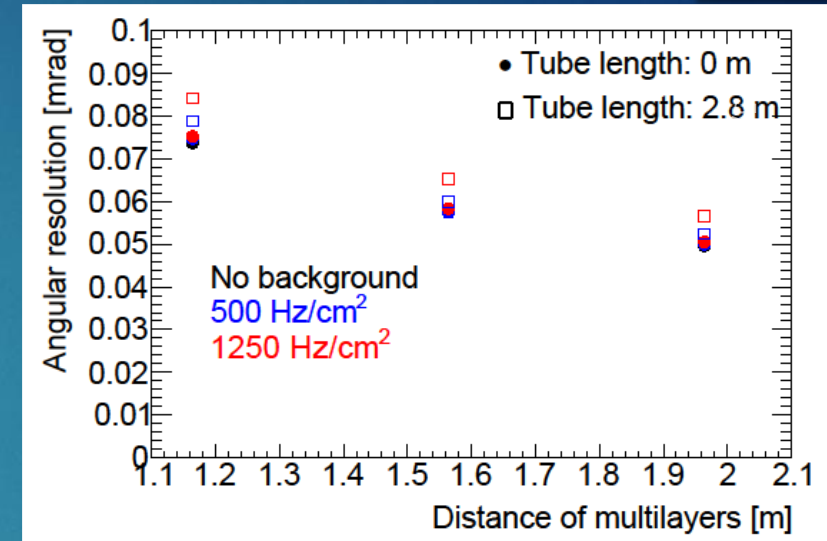
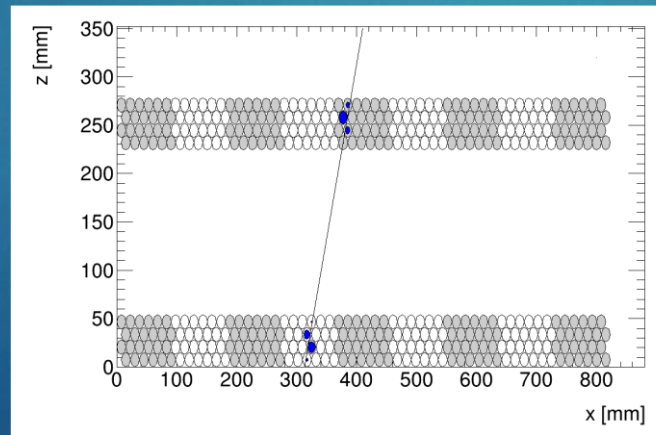
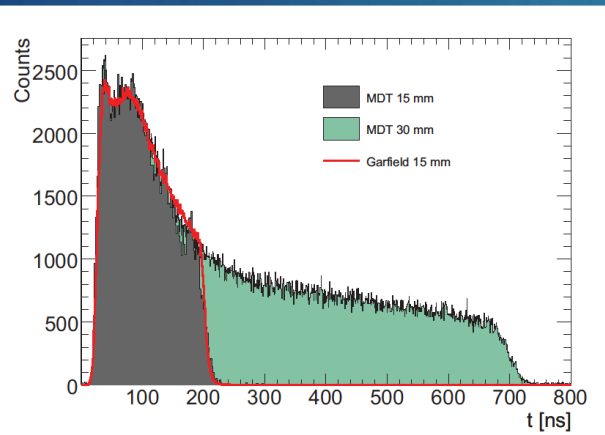


Space resolution performance

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Drift tubes (ATLAS case – CMS is similar)

- ▶ Examples: ATLAS and CMS DT systems
- ▶ Great improvement by reducing the drift length
- ▶ Wire accuracy $20\mu\text{m}$, resolution $< 80\mu\text{m}$
- ▶ Angular resolution independent on the track angle
- ▶ Self calibrating
- ▶ Angular resolution $< 70\text{ mrad}$ with 2x4 tube layers
- ▶ Mechanically stable over large areas

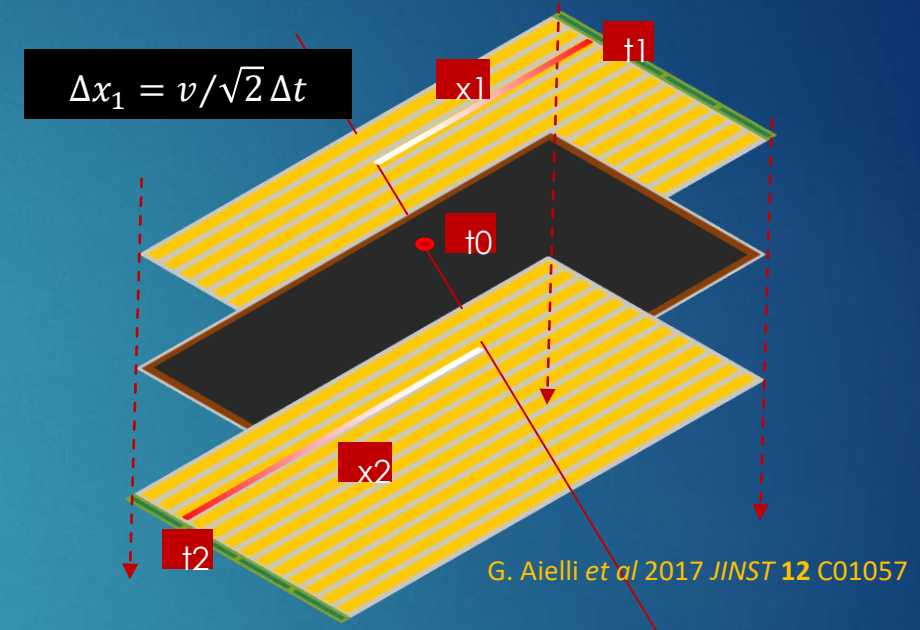


Drift tubes are at the moment a more reliable and simpler tracking technology with respect to planar detectors

Yet another method: strip drift time

CHALLENGING READOUT FOR FUTURE COLLIDERS

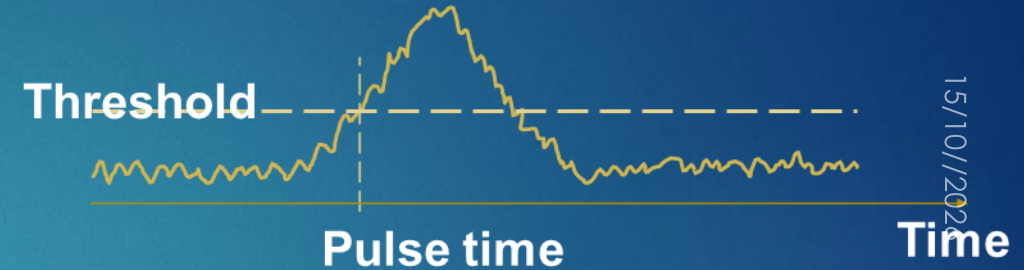
- FAST LEADING SIGNALS FOR THIN GAS GAPS
- NEW GENERATION OF INEXPENSIVE ~ 1 PS TDCs
- PROPAGATION SPEED 15 CM/NS
- 100 μM PRECISION IS THE TARGET
- CAN BE REPLICATED IN 2D
- ACCURATE RECONSTRUCTION OF MULTIPLE TRACKS



Time resolution principles

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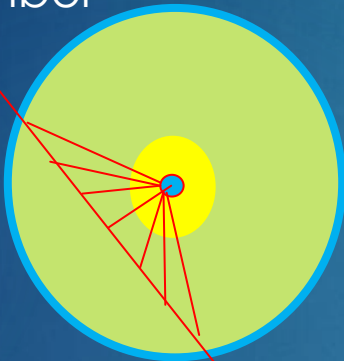
- ▶ Time resolution is driven by
 - ▶ Avalanche statistical fluctuations
 - ▶ Drift time (velocity x gap size)
 - ▶ Electronics noise



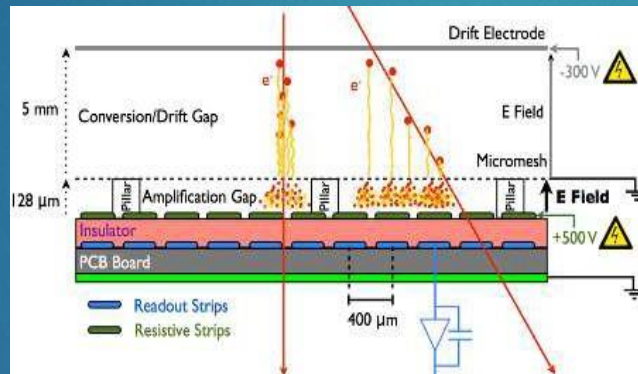
15/10/2024

Wire chamber

$$E \approx \frac{1}{r}$$



MPGD

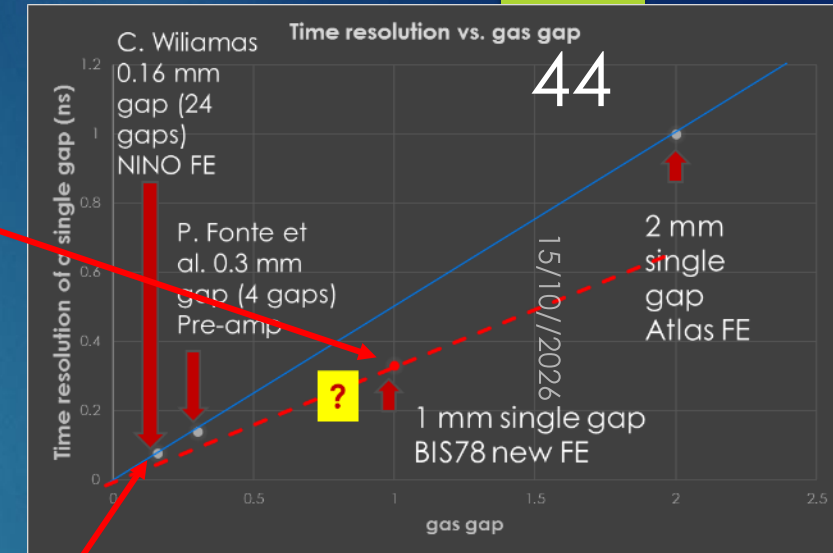
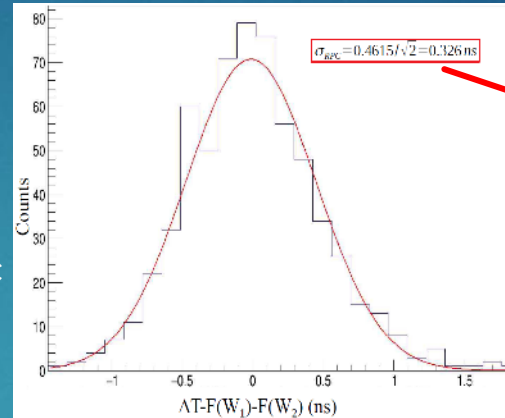


- ▶ MWPC and MPGD work on similar principles: the separation of the drift and multiplication introduces irreducible uncertainty on the time resolution, dependent on the drift width
- ▶ RPCs and MRPCs drift and multiplication space coincide. The multi-micro gap RPC segments the gas gap to further reduce the drift time

RPC time resolution

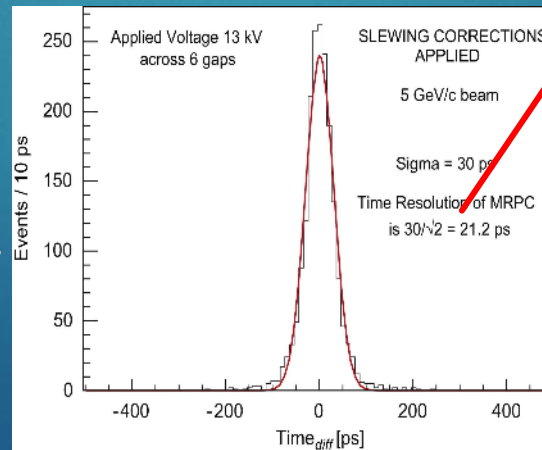
Time resolution is one of the main RPC features

- ▶ Golden standards: **MRPCs ~50 ps** -- **RPCs ~500 ps**
- ▶ complex physics behind: cluster statistics, multiplication dynamics, electronic noise
- ▶ Empirically smaller gas gaps → higher resolution
 - ▶ Smaller gas gaps can be operated at higher electric field and have a faster multiplication dynamics compressing noise fluctuations
- ▶ As one learn from other detectors the electronics noise plays a role



CHALLENGE: RESOLUTION BEYOND 50 PS

- WITH MORE AND THINNER GAS GAPS, E.G., 20 PS WITH 24, 0.16 MM GAPS
[[10.1016/J.NIMA.2008.06.013](https://arxiv.org/abs/10.1016/J.NIMA.2008.06.013)]
- THINNER ELECTRODES → HIGHER SIGNAL
- LOW NOISE HIGH RESOLUTION FEE (PICO TDC) [HTTPS://KT.CERN/TECHNOLOGIES/PICOTDC](https://kt.cern/technologies/picotdc)



INNOVATIVE APPROACH →

- GOING BEYOND THE GAS GAP WIDTH LAW
- EXTRACT HIDDEN INFORMATION BEYOND DISCR. AND SLEW CORRECTION
- PROMISING THE USE OF DNN TO FILTER THE COMPLEX AVALANCHE DYNAMICS → 16 PS ACHIEVED! [[ARXIV:2005.03903V1](https://arxiv.org/abs/2005.03903v1)] [[PHYSICS.INS-DET](https://arxiv.org/abs/2005.03903v1)] 8 MAY 2020]

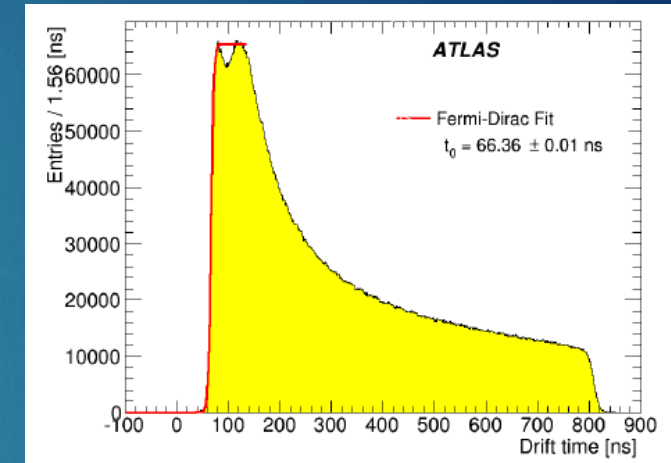
Drift based detectors time resolution

45

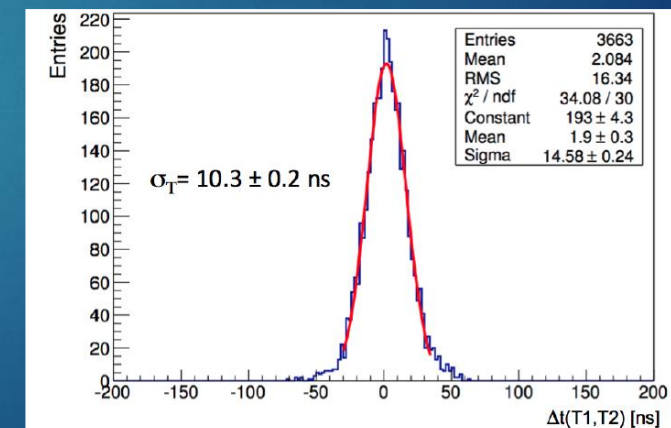
- ▶ DT drift spectrum is by construction unsuitable for timing as a long drift time is used for high space accuracy
- ▶ ATLAS Thin gap chambers $\rightarrow$ 6-7 ns
- ▶ Typical Micromegas, GEM, μ RWELL 10 ns
- ▶ A proposal to get rid of the drift variations is to hybridize a MMGAS with a photo-cathode and a Cherenkov radiator. Resolution $\sim$ 50 ps driven just by the single avalanche process, like in MRPC

- ▶ Drift detectors are limited in time resolution and an optimal strategy is combining a drift detector with an RPC to have a combined performance.
- ▶ MPGD have a barely sufficient resolution for identifying the BC at 25 ns but it can be improved by using multiple layers for the 5ns scenario

Atlas MMGAS



Atlas sMDT



Present limits – rate and longevity

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Rate capability [RPCs and MPGDs]

- ▶ Electrode resistivity to prevent discharges in RPCs and MPGDs but limits rate capability:
 - ▶ $\Delta V = \langle Q \rangle \times \text{freq.} \times R$
- ▶ $\langle Q \rangle$ is very favorable in MPGDs because the multiplication gap is fixed

Longevity: Bulk materials insensitive to radiation, but

- ▶ radicals produced in RPC avalanches
- ▶ High gain may induce discharges in MPGDs

Rate capability (drift chambers)

- ▶ Limited by the space-charge effect
- ▶ Effect reduced with $R^3 \rightarrow R=1/2 \rightarrow \text{rate} = 8x$ (drift time $\times$ cross section)

Longevity: Bulk materials insensitive to radiation, but

- ▶ Gas purity is very important to avoid ageing
- ▶ no discharges possible (geometrical quenching)
- ▶ No observed ageing in such conditions

• LOWERING R IMPROVES RATE CAPABILITY ONLY

- LOWER RESISTIVITY MATERIALS
- THINNER ELECTRODES

• ACHIEVING HIGH RATE BY BRUTE FORCE REDUCTION OF R (WITHOUT REDUCING AT THE SAME TIME THE E FIELD) MAY LEAD TO INSTABLE DETECTORS

• REDUCTION OF $\langle Q \rangle$ IMPROVES RATE CAPABILITY AND LONGEVITY AT THE SAME TIME

- BY IMPROVING THE S/N ON THE FE ELECTRONICS
- BY IMPROVING THE SIGNAL COLLECTION EFFICIENCY

Gas with reduced chemical impact on the detector bulk and clean are keys to longevity

Technology state of the art evaluation (my personal view)

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30/05/2023

Useless = *
Poor = **
Sufficient = ***
Good = ****
Excellent = *****

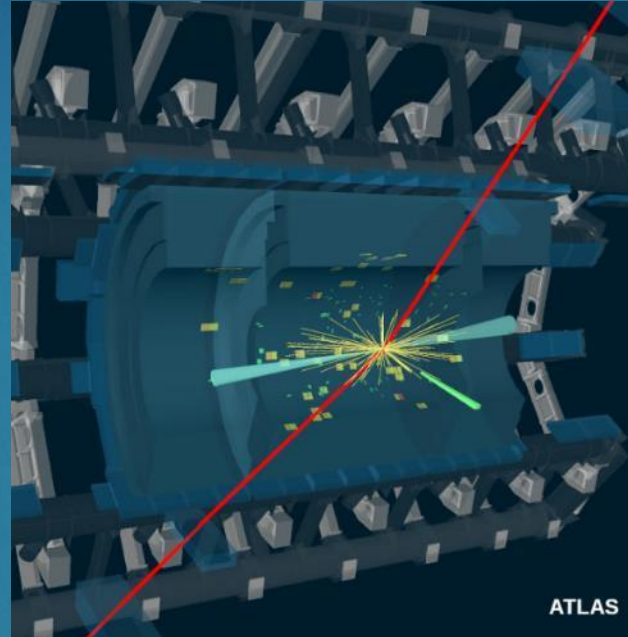
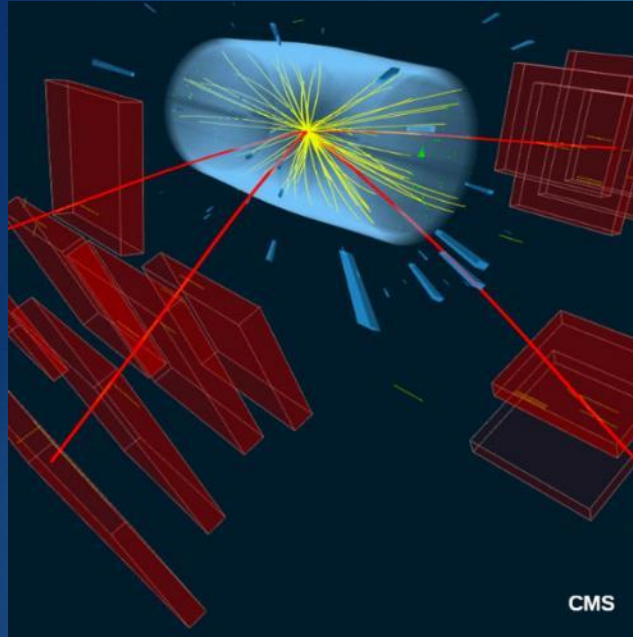
Incremental R&D = *
Disruptive R&D = *

State of the art	Rate capability	Longevity (hadrons)	Space resolution	Time Resolution	Cost	Industrialization	Scalability
DT	***	*****	*****	*	***	***	*****
sTGC	*****	***	***	***	***	**	***
RPC	***	***	***	*****	*****	***	*****
MPGD	*****	***	***	***	**	***	***
R&D potential	Rate capability	Longevity (hadrons)	Space resolution	Time Resolution	Cost	Industrialization	Scalability
DT	*****	*****	*****	**	***	*****	*****
sTGC	*****	***	*****	***	***	***	*****
RPC	*****	*****	*****	*****	*****	*****	*****
MPGD	*****	*****	*****	*****	**	*****	*****

Backup

Introduction on muon systems

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- ▶ Muon systems is whatever comes after the hadronic calorimeter, wrapping all the other detectors
- ▶ It is designed to provide a primary trigger on muons and measure their momentum spectrum
- ▶ It is done by measuring the muon trajectory deflection in a magnetic field

Typical features for HL-LHC

- ▶ measure of track curvature $\rightarrow$ thousands of m^2 instrumented surface
- ▶ Particle rate $\ll$ than innermost detectors
- ▶ Typical tracking precision $\sim 100 \mu m$ (with $B \sim 1T$ and $R=5m$)
- ▶ Typical trigger detector resolution $< 5 ns$

How this will evolve in FFC scenarios and what are the consequences on the muon detector design?

15/01/2026

Constraints from the new Accelerators

Main Cases at study

- *pp*-collider (*FCC-hh*)
- → main emphasis, defining infrastructure requirements
- **~16 T ⇒ 100 TeV *pp* in 100 km**
- ~100 km tunnel infrastructure in Geneva area, site specific
- *e⁺e⁻* collider (*FCC-ee*) as potential first step
- *p*-*e* (*FCC-he*) option, integration one IP, e from ERL
- **HE-LHC** with *FCC-hh* technology (LHC Ring 8→16T, 14→28TeV)

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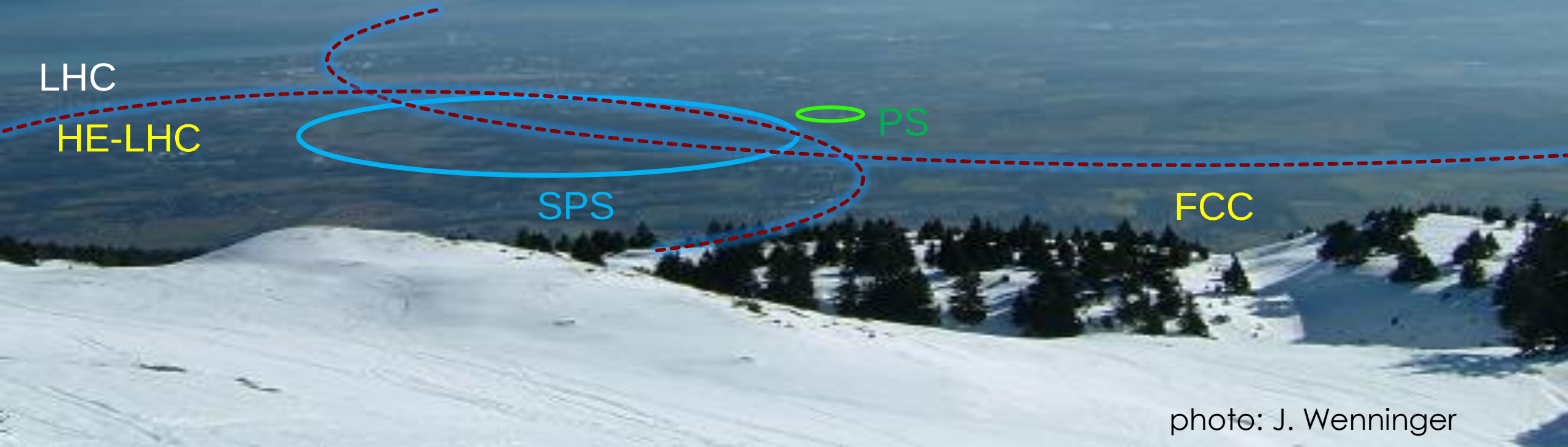


photo: J. Wenninger

FFC-hh parameters and constraints

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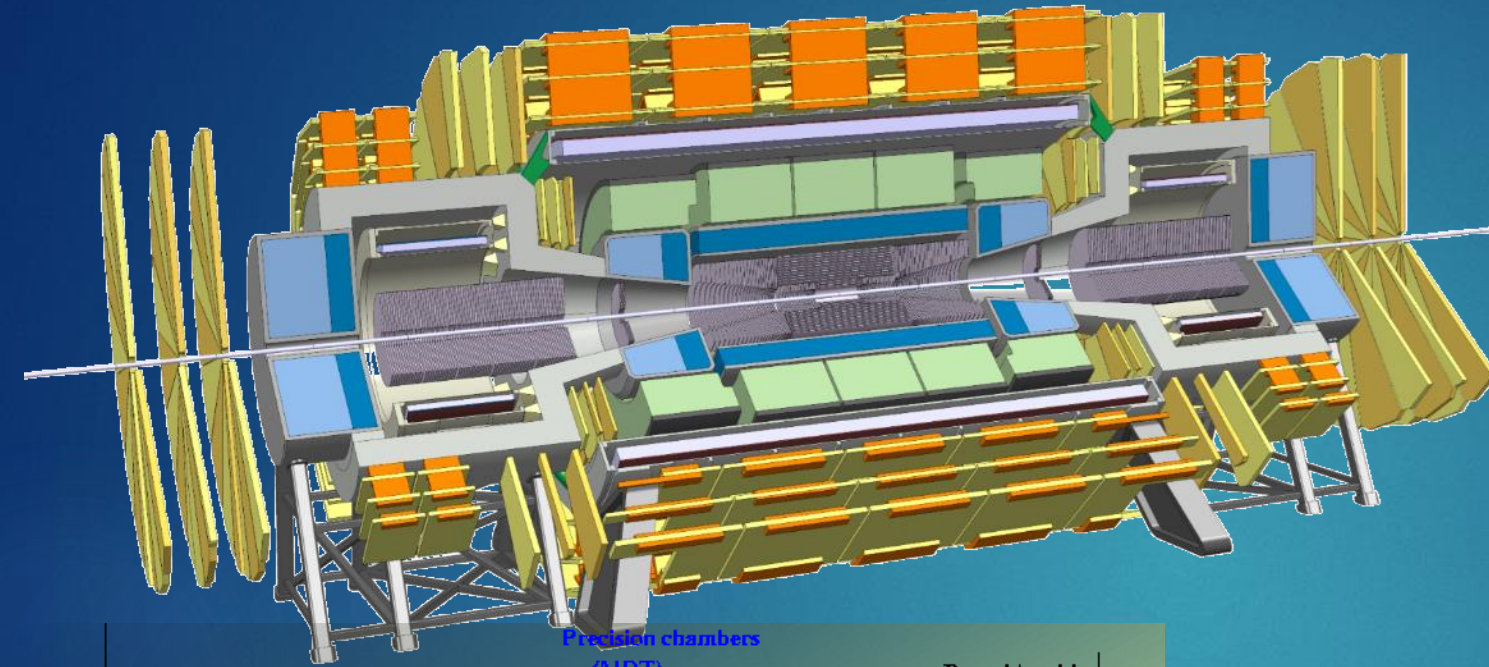
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	25	5	1
events/bunch crossing	170	1000 (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

- Constraints given by FCC-ee are less challenging for that concern the background rate and similar for the rest

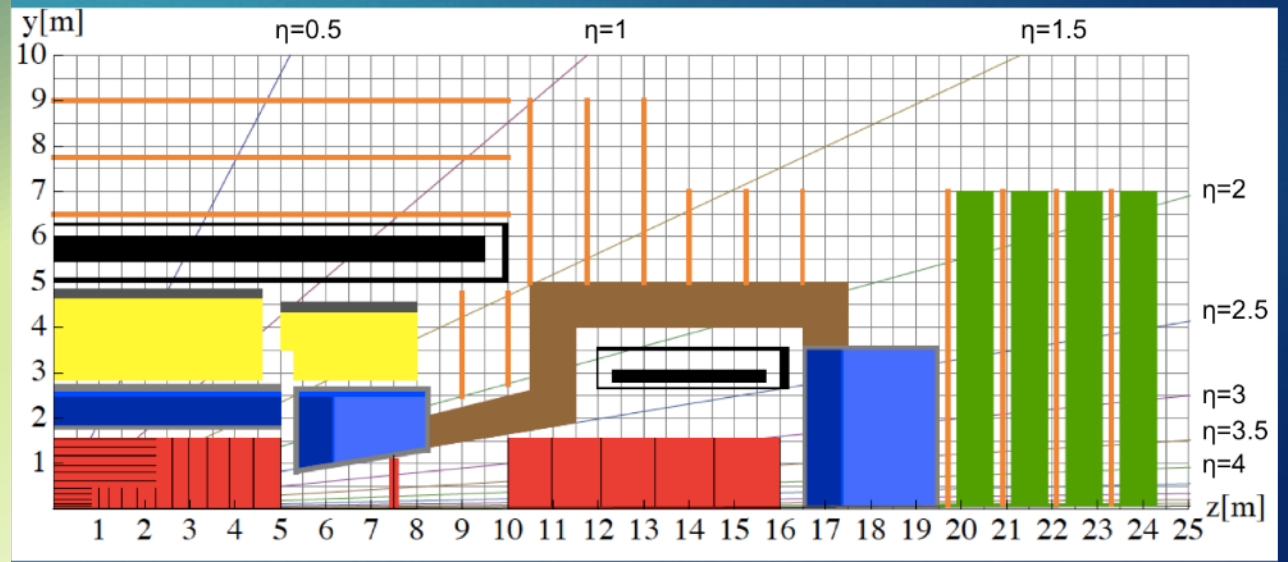
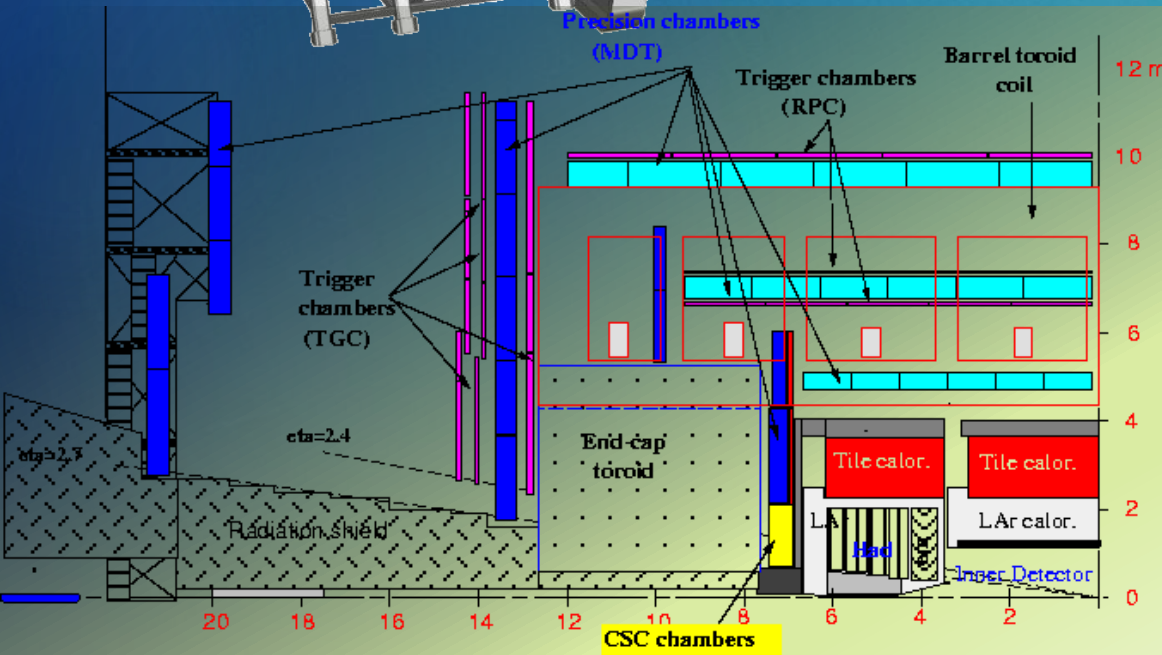
- Highlighted in red → drivers for muon systems
- A factor 6 higher average rate w.r.t HL-LHC
- Physics boosted in the forward regions → muon precision $|\eta| \sim 4$
- Combined muon tracking
- Stand-alone muon trigger
- X10 pileup → option to lower at 5 ns the BC to reduce the bunch intensity

FFC-hh reference detector

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- ▶ 4T 10m solenoid
- ▶ Forward solenoids
- ▶ Silicon tracker
- ▶ Barrel ECAL Lar
- ▶ Barrel HCAL Fe/Sci
- ▶ Endcap HCAL/ECAL Lar
- ▶ Forward HCAL/ECAL Lar
- ▶ MUONS?
1.5/1.0/1.20/2.6
Barrel
Encap
Forward
- ▶ Various gaseous detectors

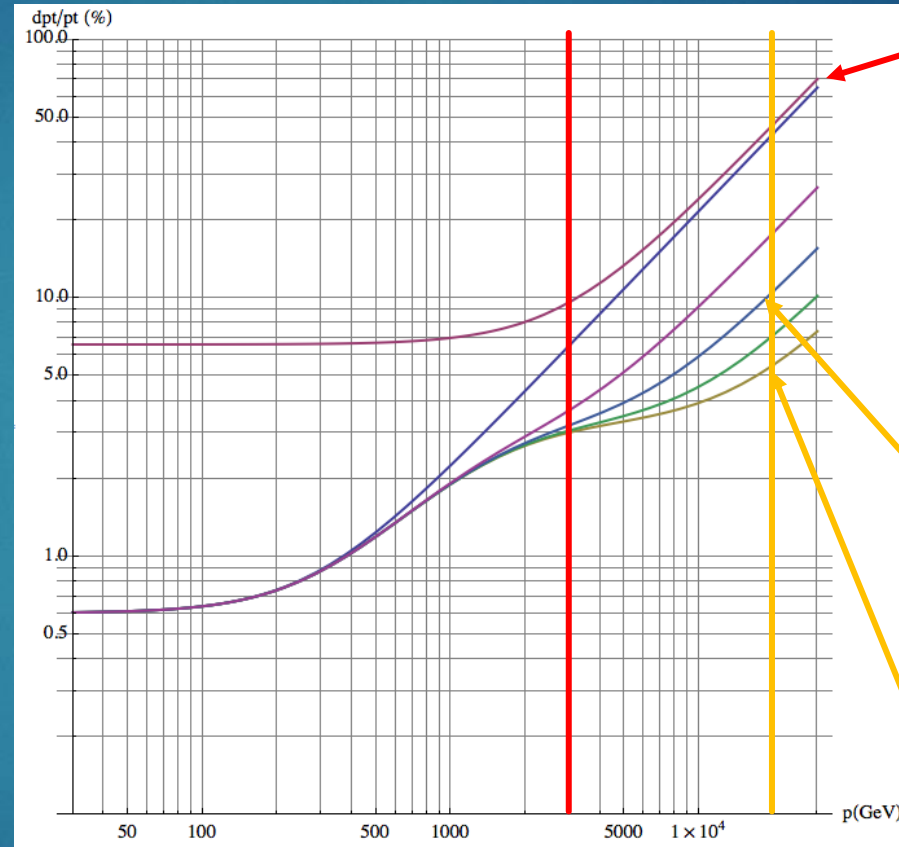
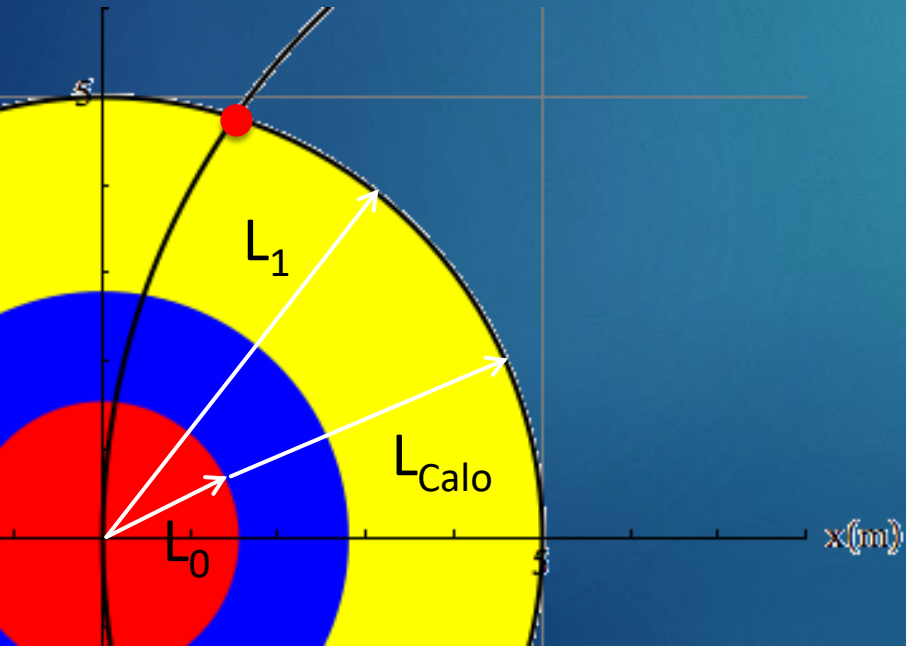


Muon tracking performance

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Three methods for the muon momentum measurement

- ▶ **Tracker only** with identification in the muon system
- ▶ **Muon system only** by measuring the muon angle where it exits the coil
- ▶ Tracker **combined** with the position of the muon where it exists the coil



Analytical calculation,
Werner Riegler, FCC Week 2017

70 μ rad muon detector angular resolution:

- ▶ < 10% standalone momentum resolution up to **3 TeV**, equal to tracker resolution

50 μ m muon detector spatial resolution:

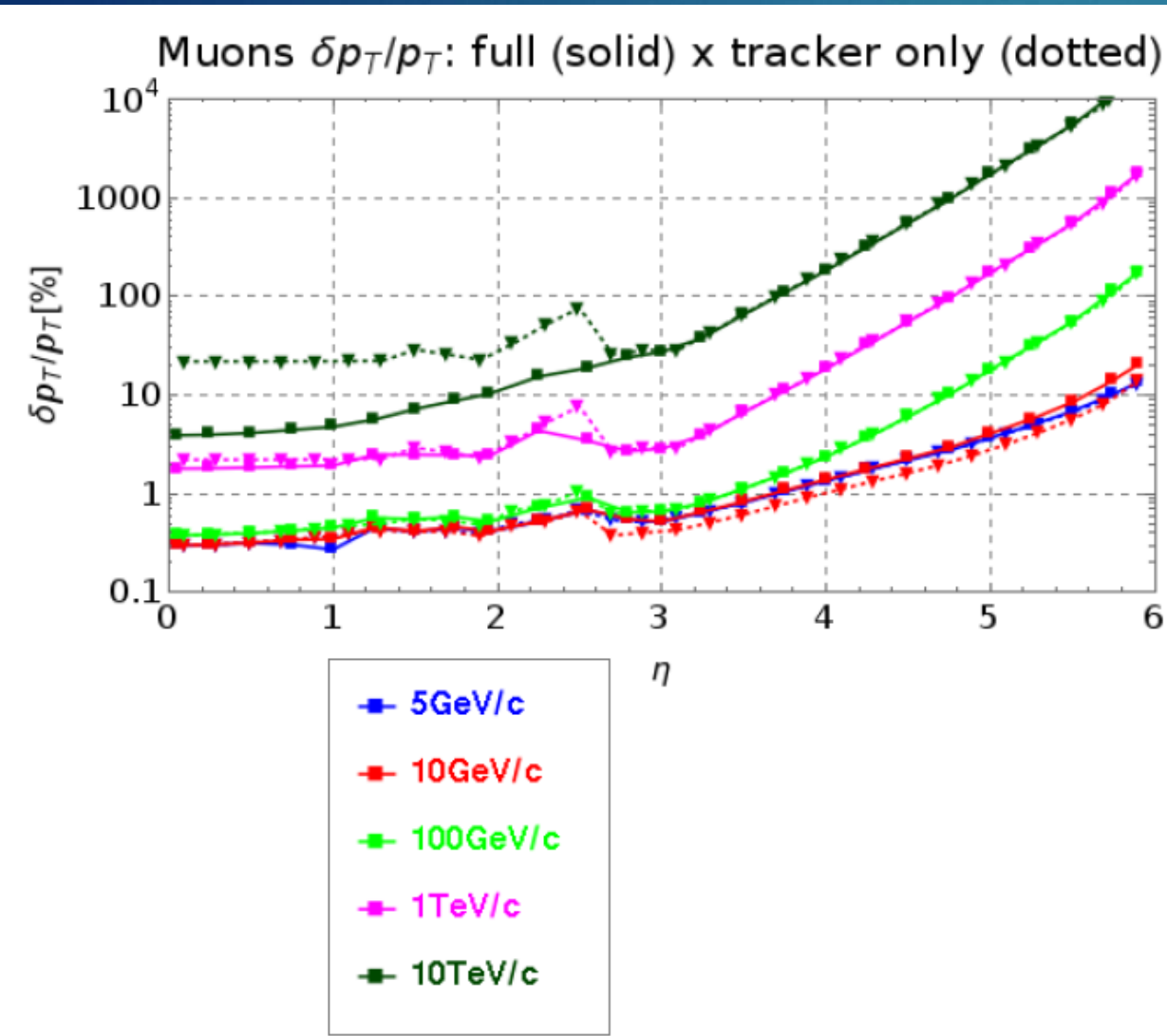
- ▶ < 10% combined momentum resolution up to **20 TeV**.

Multiple scattering limit for track combination (infinite muon detector resolution)

Muon system contribution

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Tracking

- Improvement by muon system for $p_T > 1$ TeV and $|\eta| < 2.5$.
- Muon and Barrel endcap fully included
- Forward is meant principally for muon identification

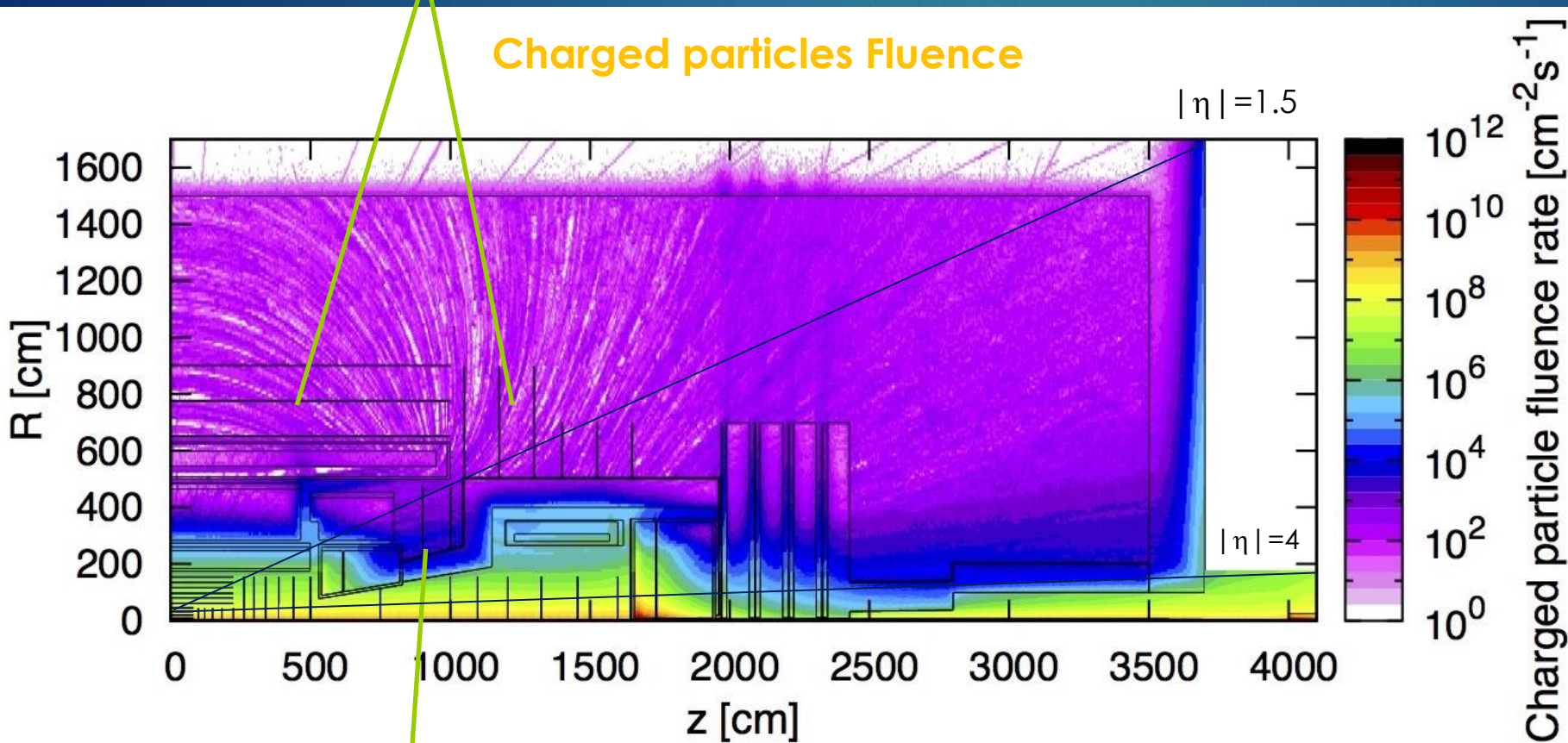
Trigger

- Momentum resolution at $p_T < 100$ GeV dominated by multiple scattering, independent of detector resolution.
- For 200 X0 of scattering material in front of the muon system and perfect chamber resolution 5 - 25% standalone p_T resolution from $\eta = 0$ up to $|\eta| = 2.5$ for 1st level muon trigger.
- Solenoidal B field in forward direction ($|\eta| > 2.5$) not suitable for precise standalone momentum measurement for trigger (p_T resolution $> 80\%$).

Particle Fluence @ $L=30 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

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- Barrel muon chambers: $\sim 300 \text{ cm}^{-2} \text{ s}^{-1}$ to $\sim 500 \text{ cm}^{-2} \text{ s}^{-1}$



Endcap Muon Chambers: $10^4 \text{ cm}^{-2} \text{ s}^{-1}$

Forward Muon Chambers: $5 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$

- Charged rates
 - Up to $500 \text{ cm}^{-2} \text{ s}^{-1}$ ($R > 3 \text{ m}$ $|\eta| < 1.5$)
 - up to $10^4 \text{ cm}^{-2} \text{ s}^{-1}$ ($R > 1 \text{ m}$ $1.5 < |\eta| < 3.5$)
 - $\sim 5 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ ($R < 1 \text{ m}$ $|\eta| > 4$)
- photon rates
 - $\sim 5 \times 10^{6-8} \text{ cm}^{-2} \text{ s}^{-1}$
- N fluence
 - Up to 10^{14} cm^{-2} (shielding to mitigate the effect)

Present muon detectors close to fully satisfy this requirement → further R&D needed for completing

Pileup of 1000 (25ns Bunchcrossing)

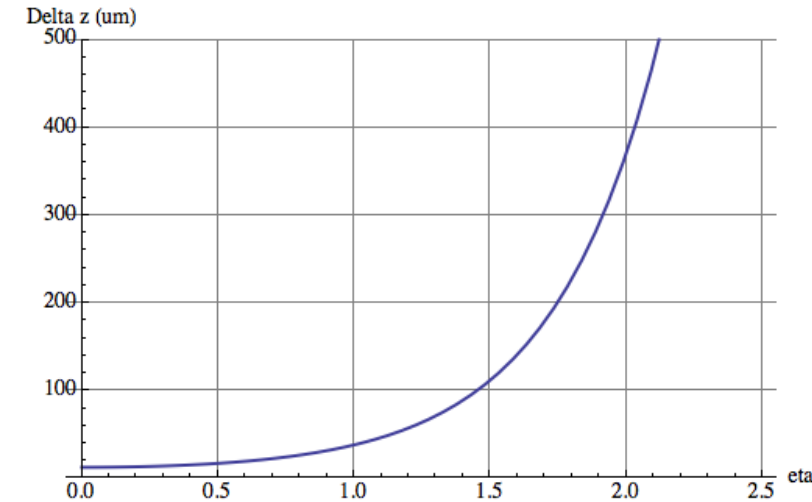
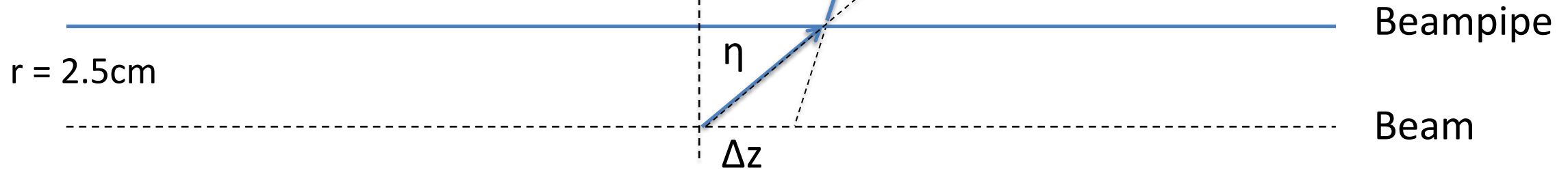


HL-LHC average distance between vertices at $z=0$ is
 $\approx 1\text{mm}$ in space and 3ps in time.

For 6 times higher luminosity at FCC-hh (an HE-LHC) this would become
 $\approx 170\mu\text{m}$ in space and 0.5ps in time.

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta_{cp}} z \sqrt{x/X_0} \left[1 + 0.038 \ln(x/X_0) \right]$$

$x=0.8\text{mm}$, $X_0=35.28\text{cm}$ (Be), $p=1\text{GeV}$



Even having a perfect tracking detector, the error due to multiple scattering in the beampipe for $\eta > 1.7$ is already larger than the average vertex distance !

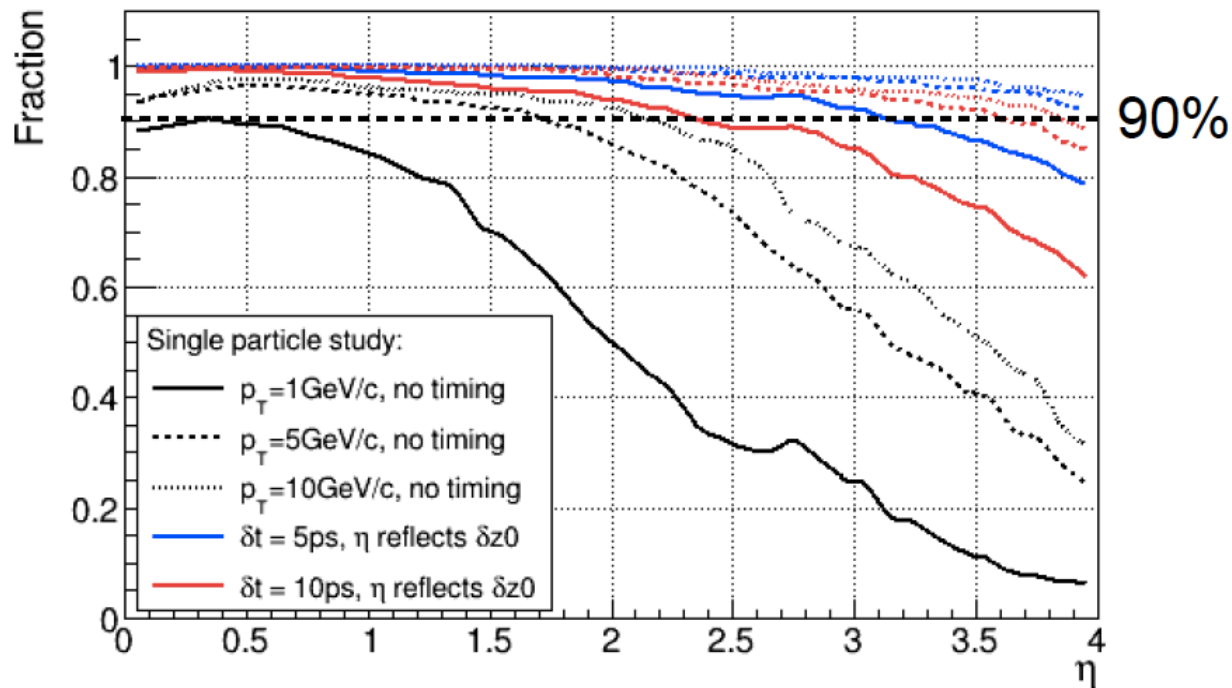
Timing, very clever new ideas needed ...

Vertexing at Pileup of 1000, Timing

→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

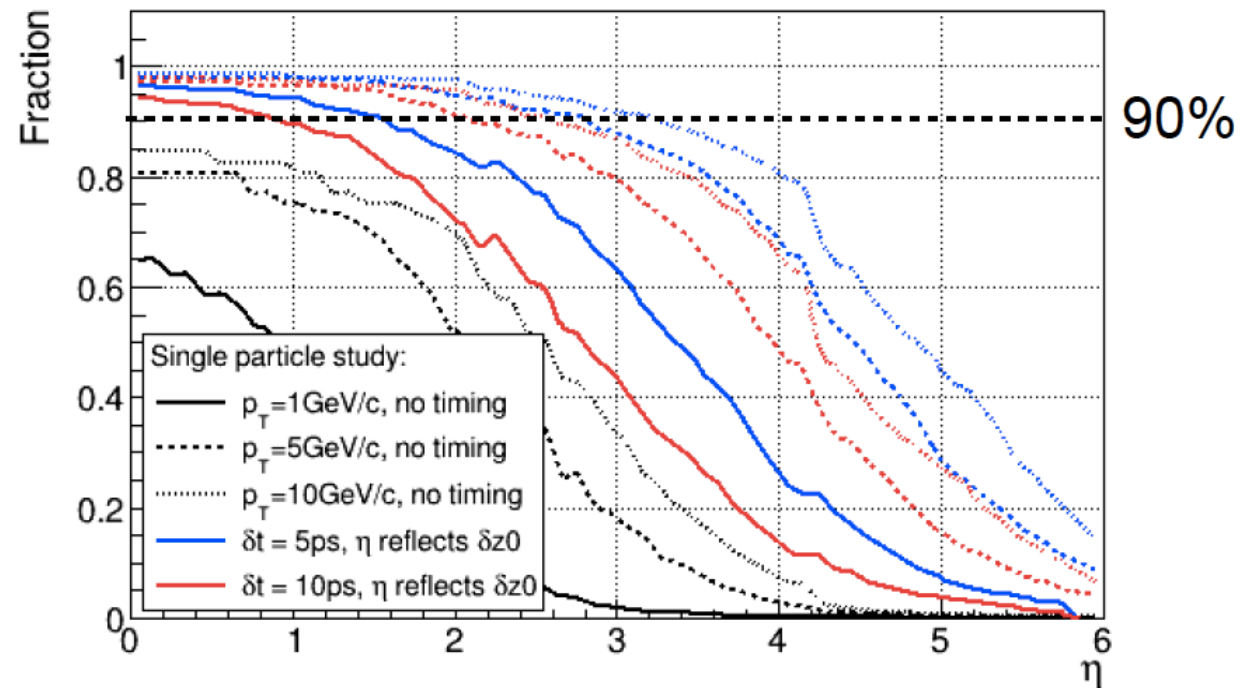
HL-LHC scenario @ PU=140 CMS Ph2 Upgr. tracker

Fraction of tracks being unambiguously assigned to PV @95% CL: $\langle \mu_{\text{tot}} \rangle = 140$



FCC-hh scenario @ PU=1000 Tilted layout

Fraction of tracks being unambiguously assigned to PV @95% CL: $\langle \mu_{\text{tot}} \rangle = 1000$



Pileup mitigation - consequences

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Note: Other Bunch Spacings

Identified three main alternative scenarios, but need to study them

	Initial	Nominal	Opt 1	Opt 2	Opt 3
Bunch spacing [ns]	25	25	12.5	5	5
Protons per bunch [10^{11}]	1	1	0.5	0.2	0.2
Init. hor. transv. emittance [μm]	2.2	2.2	1.1	1.1	0.44
Init. vert. transv. emittance [μm]	2.2	2.2	1.1	1.1	0.44
Final hor. transv. emittance [μm]	1.28	0.29	0.25	0.22	0.22
Final vert. transv. emittance [μm]	1.28	0.29	0.2	0.17	0.17
Max. total beam-beam			0.03	0.03	0.03
IP beta-function [m]			0.3	0.3	0.3
Peak luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	5.01	25.2	23.2	14.5	20.1
Max. number events per crossing	170	857	394	99	137
Optimum integrated luminosity / day [fb^{-1}]	2.27	8.2	7.5	5.5	6.2

Much more study is required before we can conclude

15/10/2026

- ▶ Shorter BC spacing proposal: 12.5 and 5 ns
- ▶ Correspondingly lower bunch intensity
- ▶ Pileup reduction
- ▶ Most of internal detector are developing at least sub ns timing
- ▶ The BC id. Will require sub-ns timing in the muon system too

- ▶ At the moment just RPCs can provide this performance among the classical muon detectors → drive of new R&D effort

Constraints from LLP and DM searches

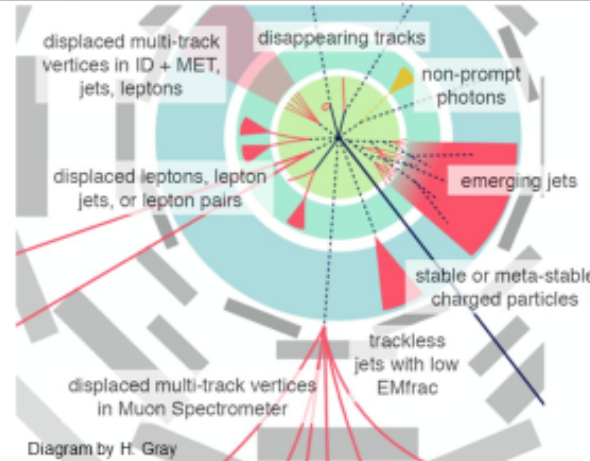
Beyond the muon detector: LLPs

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Why, how, where LLPs?

- Small couplings or small mass differences generically lead to LLPs
- Exact signature depends on LLP quantum numbers and decay modes → many possibilities, necessary to understand experimental sensitivity to these
- FCC-ee: charge, color neutral initial state → direct production of charge, color neutral BSM particles/ final states
 - Light color, electrically charged BSM particles heavily constrained
 - Consider looking for charge, color neutral particle
 - Displaced vertex signature
- FCC-hh: possible to also probe charged/colored BSM particles
 - Disappearing tracks
 - (Heavy) Heavy stable charged particles, stopped particles, R-hadrons as possible signatures
 - These exotic signatures are not covered in this talk



LLPs can also be looked for in MET and prompt final states

See talk by R. Gonzalez Suarez
See talks in the morning session

- ▶ Detector for long-lived particles at high energy of 100 TeV
- ▶ Has ca 500 times more sensitivity; 150 due to increased cross section and luminosity and factor 3-4 due to moving detector closer to IP

Impact on the muon system

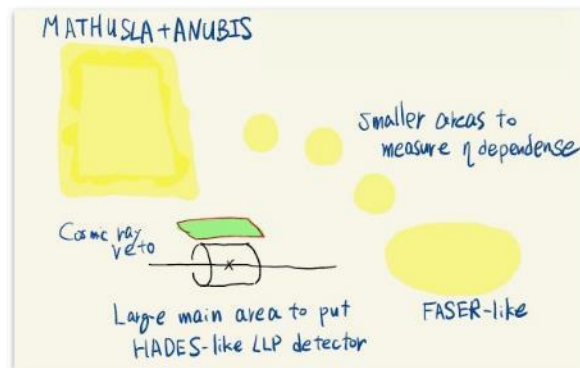
- ▶ Local vertex identification
- ▶ 3D tracking
- ▶ ~ 100 ps ToF capabilities

A dream LLP detector?

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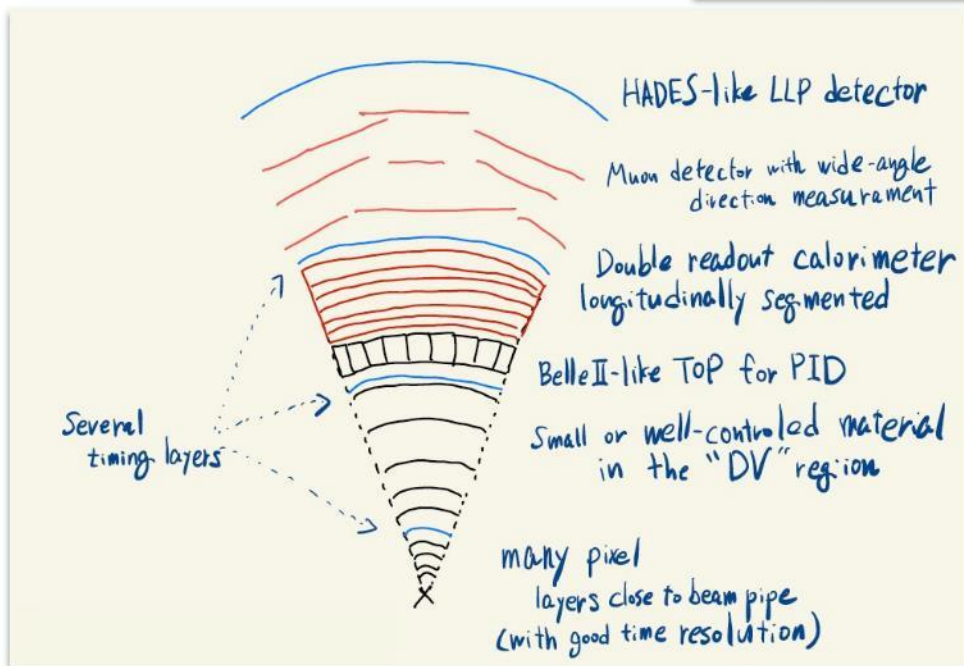
A dream LLP detector?

Ryu Sawada's first example at the LLP workshop in November-2020



Adding a good timing and tracking layer extending the muon system...

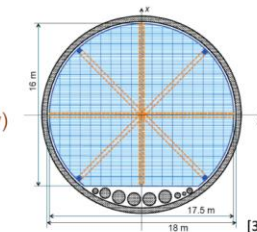
5/10/2026



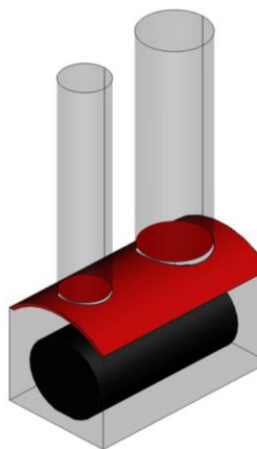
Dedicated detectors: ANUBIS

ANUBIS – AN Underground Belayed In-Shaft search experiment

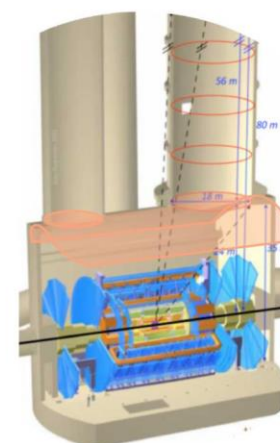
- Proposal to instrument the ceiling of the ATLAS Cavern at Point-1
 - > Include stations in the two service shafts (PX14, PX16)
 - > Ceiling approximately 20m away from the ATLAS IP
 - > Cavern ceiling proposal shown to be more sensitive (compared to Shaft only)
 - > Larger active volume ($4.3 \times 10^4 \text{ m}^3$ vs $1.3 \times 10^4 \text{ m}^3$) and large detector area $\sim 10^3 \text{ m}^2$



PX14 Shaft: Cross sectional view [3]



Proposal



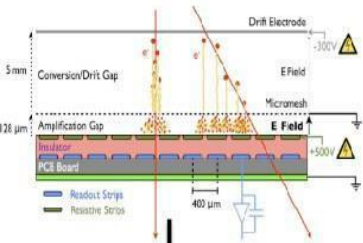
arXiv:1909.13022

<https://twiki.cern.ch/twiki/bin/view/ANUBIS>



PX14 Shaft + Ceiling

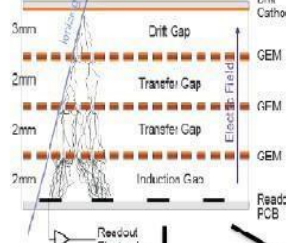
MicroMegas (MM)



ATLAS new small wheels



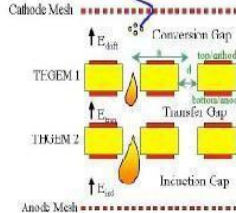
GEM



CMS GEM



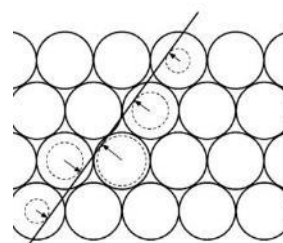
THGEM



ALICE TPC upgrade



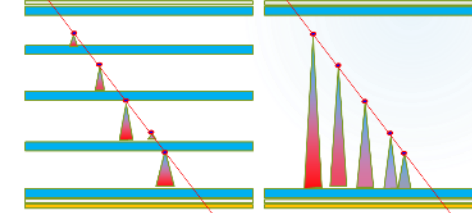
sMDT



ATLAS Ph1 + Ph2 upgrade



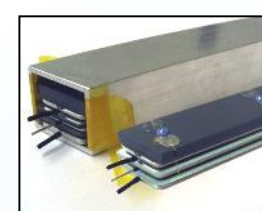
RPC



ATLAS Ph1 + Ph2 upgrade and CMS RE3/1 & RE4/1



Several experiments at GSI and RICH

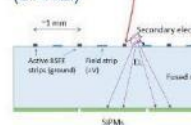


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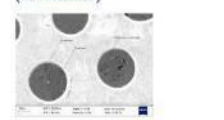
Muon detector technologies

AND NEW IDEAS

Positive Ion Detection in gaseous TPC (L. Arazi)



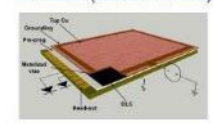
Charge transfer properties through graphene (P. Thüner)



3D printed THGEM (F. Brunbauer)



uRWELL (G. Bencivenni)



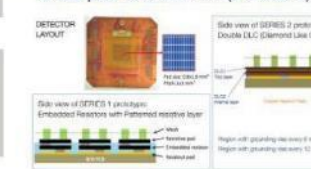
Scream mm (M. Chefdeville)



PICOSEC mm (PICOSEC coll.)



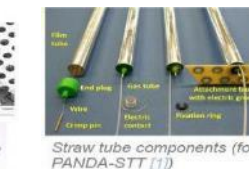
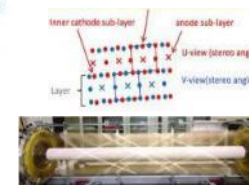
Small pad resistive mm (M. Iodice)



COMPASS RICH-1 (Compass)



GridPix (J. Kaminski)



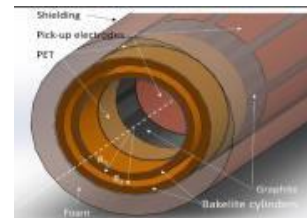
Straw tube components (for PANDA-STT [1])

sRPC (Bencivenni)

single gap semi-conductor
R. Cardarelli



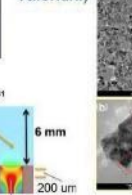
RCC Cardarelli



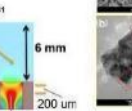
Bubble-assisted Liquid Hole-Multipliers (E. Erdal)



Nanodiamond photocathode (A. Valentini)



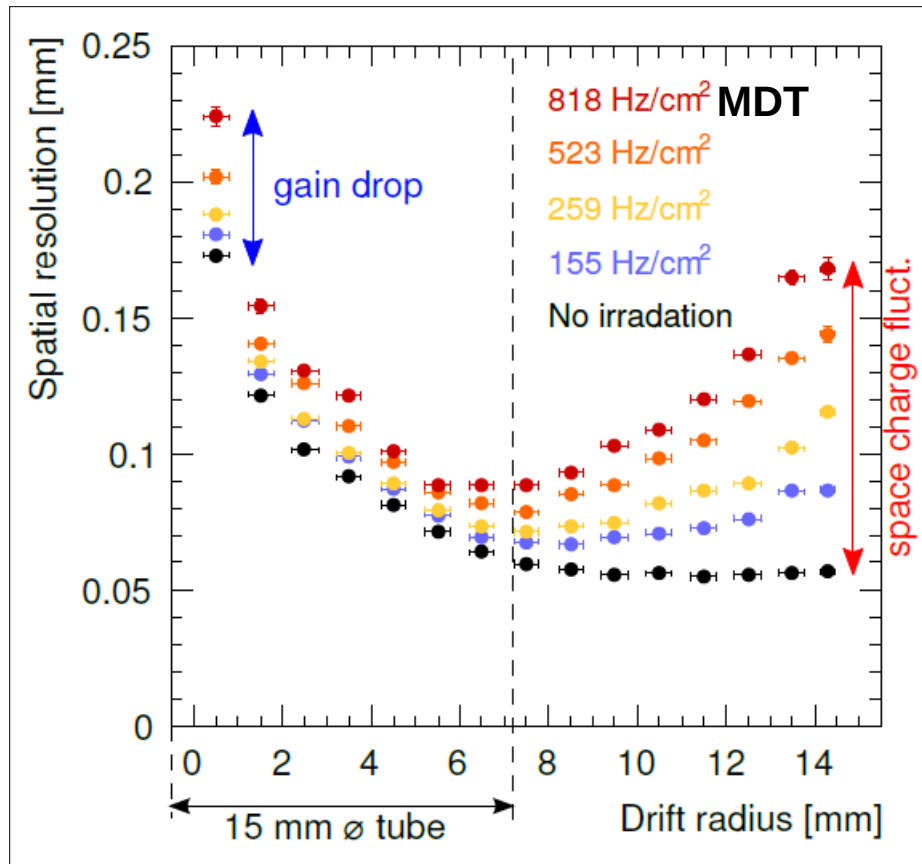
TIP-HOLE prototype (M. Cortesi)



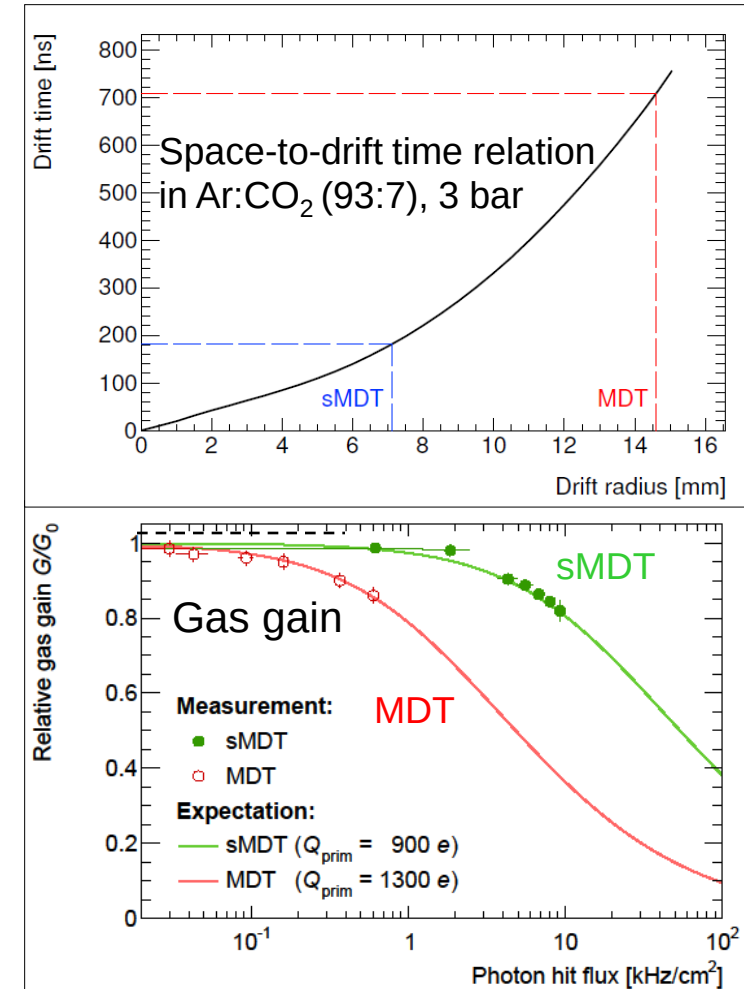
sMDT Rate Capability

15 mm tube diameter, optimum for aluminum drift tube technology at high rates:

- Effect of space charge fluctuations eliminated for drift radii $r < 7.1$ mm (linear r-t relation).
- Gain loss suppressed proportional to r^3 , i.e. by factor 8 compared to MDTs.
- 4 x shorter max. drift time, 2 x smaller tube cross section, i.e. 8 x lower occupancy.



Measurements performed at the CERN Gamma Irradiation Facility.



- ▶ Most of the FFC-hh requirements on muon detectors are fulfilled
- ▶ In the regions with higher radiation a substantial improvement is needed
- ▶ Potential competitor: new generation of Si detectors
- ▶ Fine timing is needed in the 5 ns BC scenario and for the LLP searches
- ▶ Muon detector community is sparring new ideas

Conclusion block (spoiler...)

R&D summary

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

Technology state of the art evaluation (my personal view)

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15/10/2026

Useless = *
Poor = **
Sufficient = ***
Good = ****
Excellent = *****

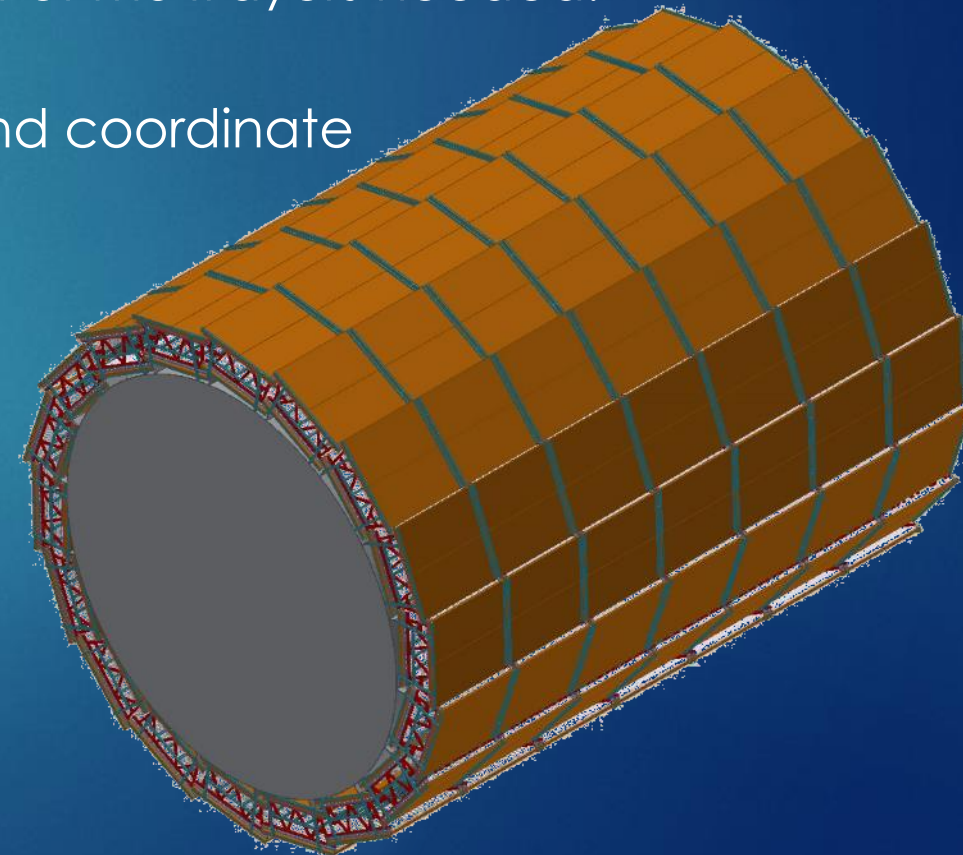
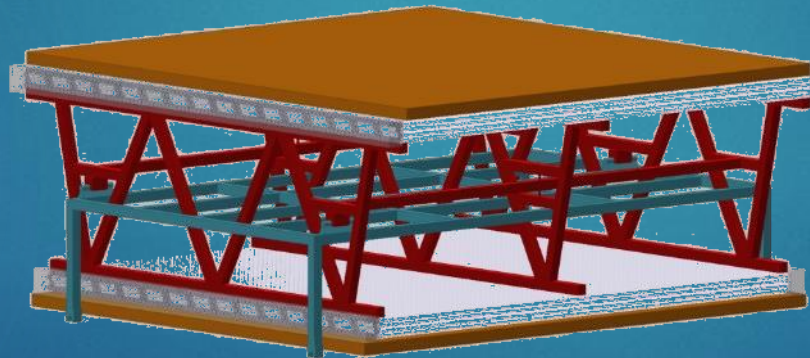
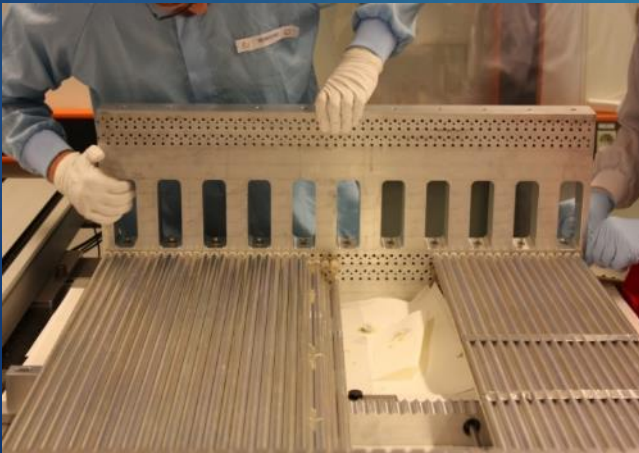
Incremental R&D = *
Disruptive R&D = *

State of the art	Rate capability	Longevity (hadrons)	Space resolution	Time Resolution	Cost	Industrialization	Scalability
DT	***	*****	*****	*	***	*****	*****
sTGC	*****	***	***	***	***	**	*****
RPC	***	***	***	*****	*****	*****	*****
MPGD	*****	***	***	***	**	***	***
R&D potential	Rate capability	Longevity (hadrons)	Space resolution	Time Resolution	Cost	Industrialization	Scalability
DT	***	*****	*****	* *	***	*****	*****
sTGC	*****	***	**** *	***	***	*** *	***** *
RPC	**** *	**** *	**** *	*****	*****	*****	***** *
MPGD	***** *	**** *	**** *	**** *	**	**** *	**** *

A working proposal (doable now)

67

- ▶ **Barrel and outer endcaps of FFC-hh:**
- ▶ 2 x 4 layers of 2.8 m long drift tubes (axial in barrel, radial in outer endcaps) with 1.4 m multilayer distance provide 40 μm spatial resolution, 60 μrad angular resolution, 100% tracking efficiency up to the maximum background rates.
- ▶ Monolithic sMDT construction, no optical alignment of multilayers needed. Chambers well accessible.
- ▶ Embedded new RPCs for trigger, timing, and second coordinate



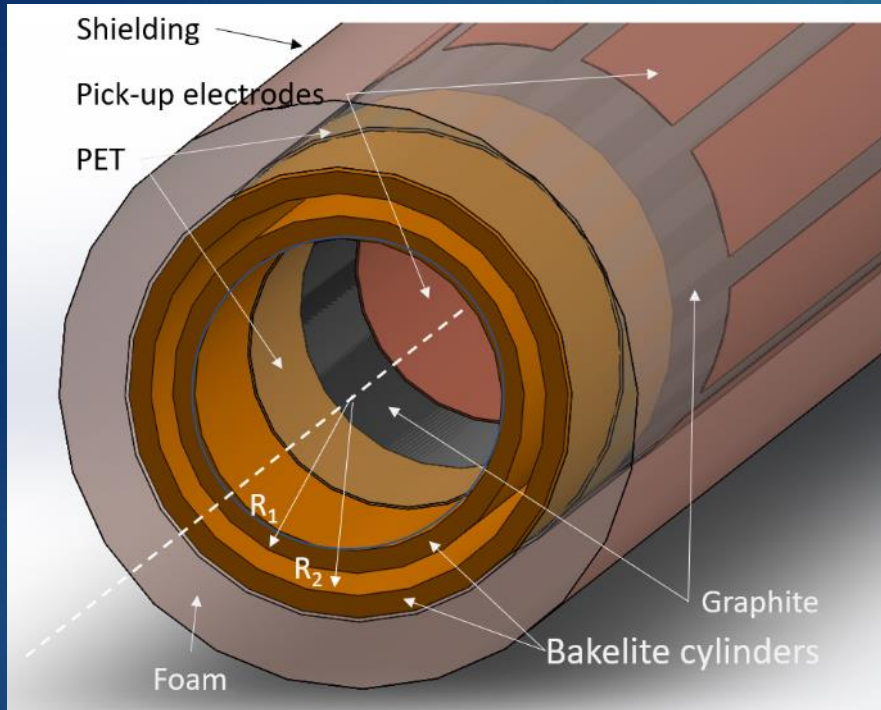
10/10/2026



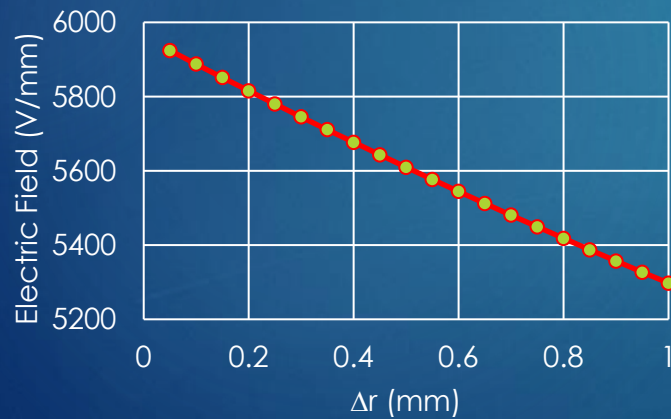
New Ideas

The Resistive Cylindrical Chamber (RCC)

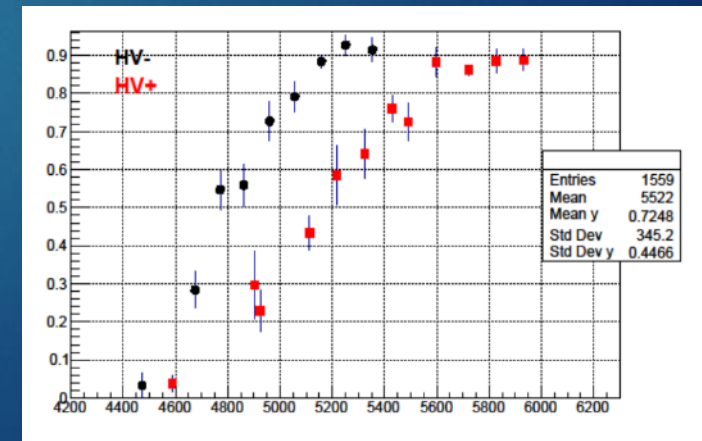
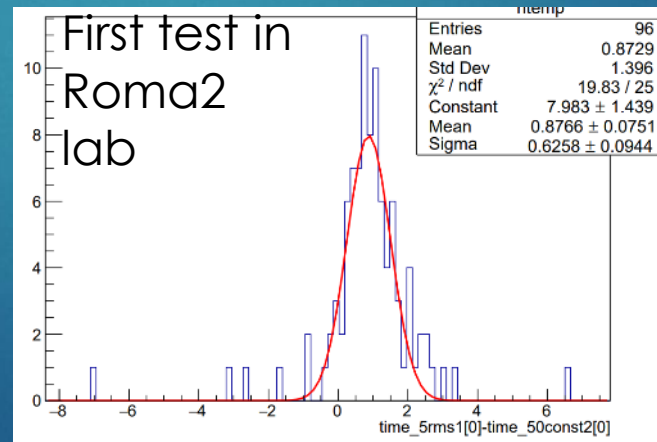
R. Cardarelli "Future RPC developments", RPC2020 Roma 10-14 /02/2020 proceeding on JINST



- ▶ Geometry defined by two concentric pipes spaced by a gas gap
- ▶ The radial field introduce the concept of geometrical quenching, can be tuned by playing with R1 and R2
- ▶ No need of expensive and high GWP electronegative gases to keep the avalanche stable
- ▶ No chemical driven ageing effects
- ▶ Cylindrical geometry supports high pressure operation i.e.
 - ▶ Full efficiency in a single micro gap even with light gases
 - ▶ Time resolution proportional to pressure
 - ▶ Can exploit large experience in MDT chambers...
- ▶ Aiming to a fully efficient sparkles ~5 ps resolution detector...
- ▶ Can be combined with a sMDT tube by adding a wire...



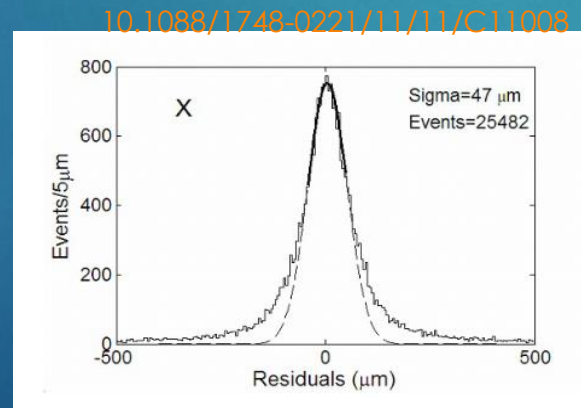
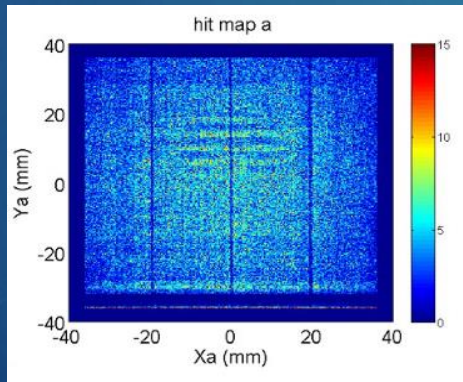
$$E(r) = -\frac{V}{r \log \frac{R_1}{R_2}}$$



13/10/2026

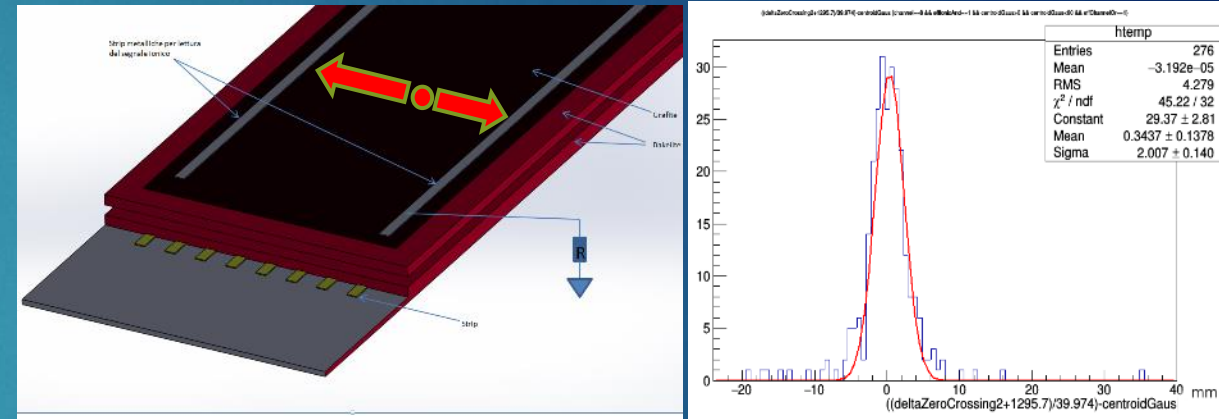
A new method: the planar drift chamber

- ▶ Planar detectors can generate signals with accurate position information → discharge cell footprint $\sim 100\mu\text{m}^2$ (10.1088/1748-0221/7/11/P11012)
- ▶ Same limitations of micro-pattern detectors coming from
 - ▶ the readout system precision
 - ▶ Expensive readout electronics
 - ▶ A lot of readout channels
- ▶ Efficient and innovative readout systems
- ▶ Applications: PET, muon tomography, future tracking devices



A NEW IDEA → PLANAR DRIFT CHAMBER

- MEASURING THE IMPACT POSITION FROM THE DIFFUSION WAVE TIME WALK DIFFERENCE ON THE GRAPHITE ELECTRODE

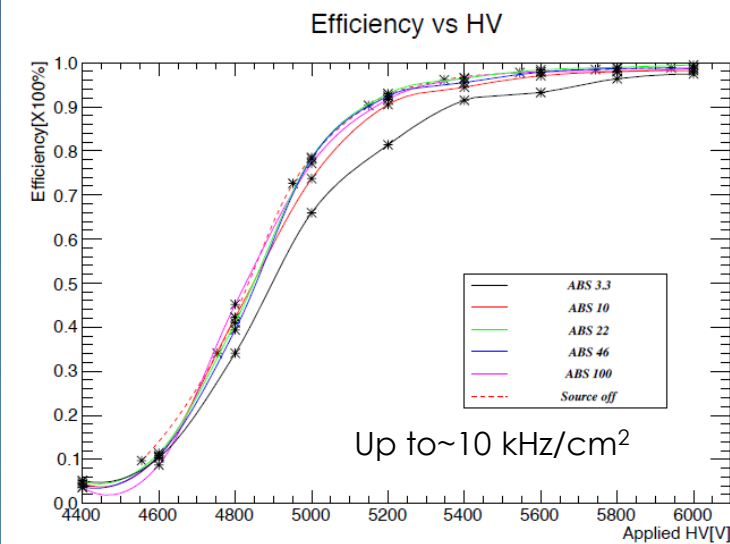


R. Cardarelli et Al. Track resolution in the RPC chamber NIM A572, vol. 1 170-172 (2007).

- CAN REACH SUB MM PRECISION
- SUITABLE FOR LARGE AREA LOW RATE ENVIRONMENT (RATE IS LIMITED TO ABOUT 100 Hz/cm²)
- VERY LOW COST READOUT ELECTRONICS

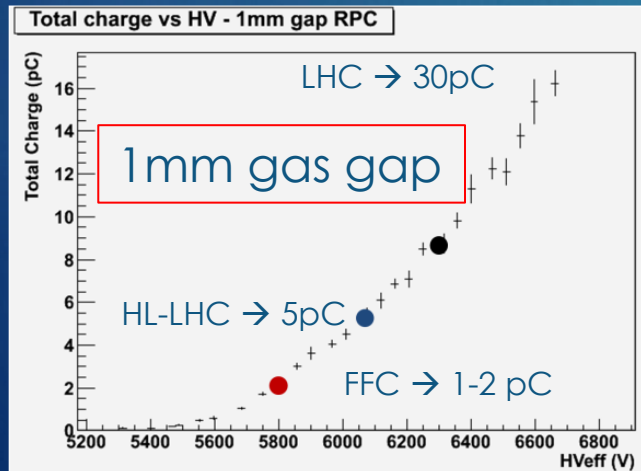
High rate for single gap RPCs

- ▶ limited by Ramo theorem ($\sim 1/20$ of $\langle Q \rangle$ is usable)
- ▶ low resistivity electrodes made of HPL ($\sim 10^{10} \Omega \text{ cm}$)
- ▶ SiGe FE tech. with 4k e- noise to reduce $\langle Q \rangle$
- ▶ Reaching up to 10 kHz/cm² in production chambers
- ▶ Suitable for safe operation with eco-gas mixture



FFC full TARGET $\rightarrow$ improve by a further order of magnitude by increasing S/N and lowering R:

Last generation SiGe hetero-junction technologies (ft 0.7 THz) announce a further $\times 10$ leap in the FE $\rightarrow$ 500 e- noise reduction

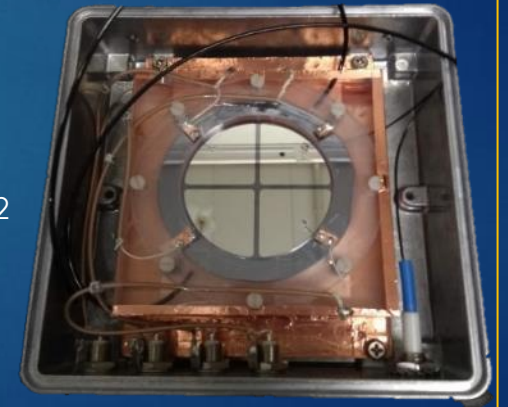


For further exploiting the electronics:

- Faster avalanche
- Very efficient grounding

A new device: single gap semi-conductor RPC
[electronic carriers can not be depleted]

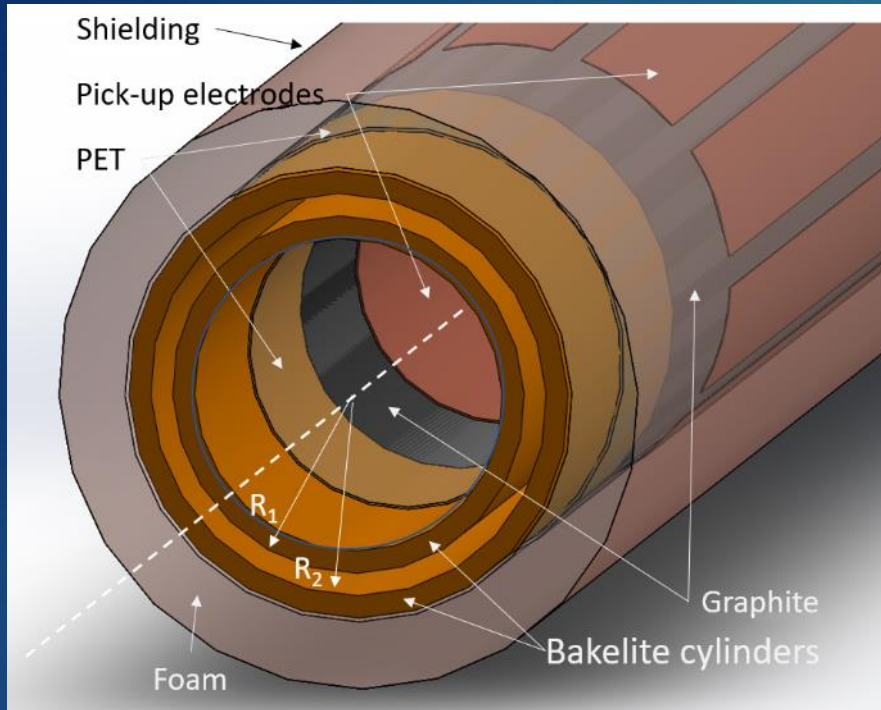
- ▶ 0.6 mm GaAs electrodes
- ▶ Resistivity $1.4 \times 10^8 \Omega \text{ cm}$
- ▶ Tested up to $> 40 \text{ kHz/cm}^2$
- ▶ $> 1 \text{ MHz/cm}^2$ is possible
- ▶ Active area 6.25 cm^2
- ▶ [10.1088/1748-0221/15/12/C12004](https://doi.org/10.1088/1748-0221/15/12/C12004)



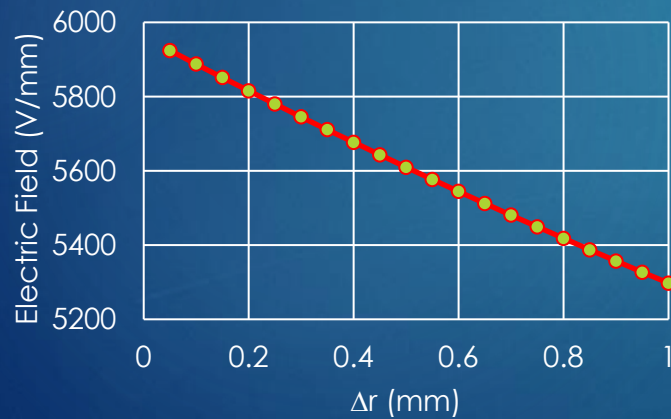
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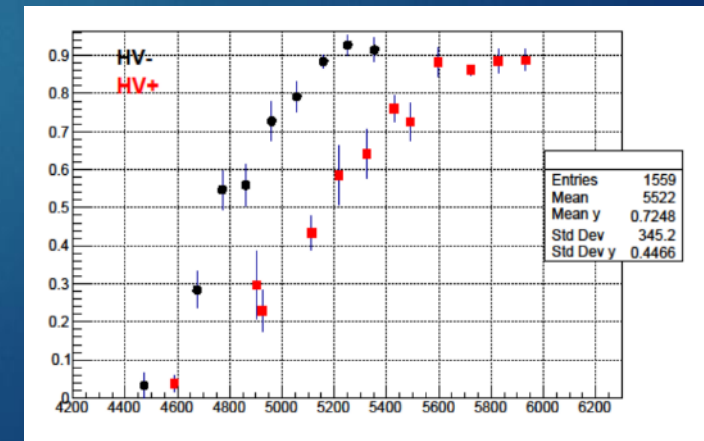
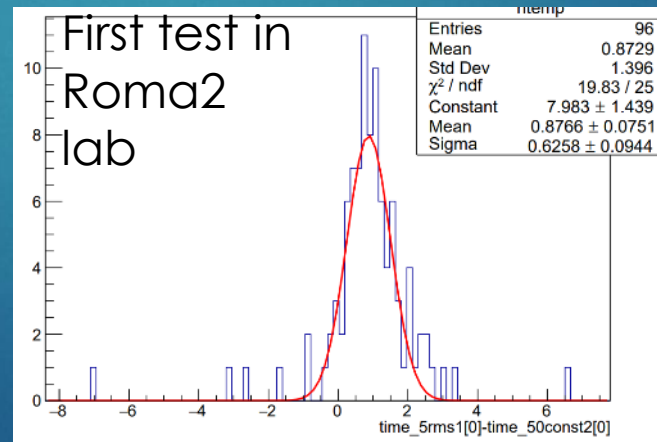
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13/10/2026