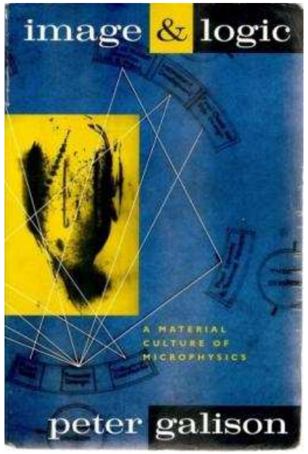
Lecture 2

Detector Instrumentation

Detector Systems design + Gas Detectors



Reference:

Peter Galison: 'Image & Logic: A material culture of microphysics'

(an entertaining history of detector physics - ~ 100AD to present contains substantial technical detail)

Review of Lecture 1

<u>Today:</u>

- Detector Systems design constraints
- How detector systems are designed to beat these constraints
- Gas avalanche detectors

What are the commonly observed particles in a detector ?

1. From the ~ 200 fundamental particles listed by the PDG, only **27** have a $c\gamma\tau > \sim 1\mu m$ so they can be seen as 'tracks' in a detector.

2. **13** of these have a $c\gamma\tau < 500\ \mu m$, *i.e. very short tracks* that must be measured indirectly with high precision vertex detectors.

3. Of the **14** remaining particles only **8** typically have energies high enough to have $c\gamma\tau >$ *few tens of meters* to make it all the way through most detectors:

$$e^{\pm}, \mu^{\pm}, \gamma^{0}, \pi^{\pm}, K^{\pm}, K^{0}, p^{\pm}, n$$

These are the common 'bread and butter' of particle physics.

What are the measurements we make?

- **Energy *E***

  through energy deposition and/or calorimetry

- **Momentum *p***

  make charged particles bend in a magnetic field

- $(E^2 - p^2) = m^2$ uniquely identifies particles

- Can also measure spin, polarization in specialized experiments.

How fast do we need to make these measurements ?

Rate of collisions $\rightarrow s^{-1}$ $$\frac{dN_{coll}}{dt} = L \cdot \sigma$$

$L \rightarrow$ *luminosity* $cm^{-2}s^{-1}$: *'brightness of the beam spots at collision vertex'*

$L = \frac{N^2 f}{A}$ for two bunched collider beams with N particles/bunch, cross-section A, colliding at frequency f

LHC at startup : $L \sim 10^{33}\ cm^{-2}s^{-1}$ *(10^{34} max)*

$\sigma \rightarrow$ *cross-section* cm^2 *: [area] – a function of particle energy!*

σ_{inel}	*'probability of collision' – inelastic collision of proton on proton*
$>\sigma_{asymm}$	*collision of electron on proton – not so trivial*
$>>\sigma_{rare}$	*rare events like production of top quark, Higgs boson – very non-trivial!*

LHC 14 TeV p+p : $\sigma_{inel} \sim 10^{-26}\ cm^2$

$$\Rightarrow \text{LHC}: \frac{dN_{coll}}{dt} \approx 10\ MHz$$

Errata:
These numbers are "order of magnitude" $\sigma_{inel} = 6 \times 10^{-26}\ cm^2$ *and only every alternate bunch is filled with protons. See LHC webpage for details*

Why is 10 MHz collision rate a problem?

The two particle physics detectors at LHC have ~ 100 million readout channels:

ATLAS – 160M

CMS – 76M

Worst case: each channel's analog signal is digitized by a 2-byte ADC

⟶ each experiment produces

100M x 2 ~ 200MB data at 10 MHz i.e. every 100 ns

or ~ 2 GB data every second

or ~ 1 DVD every 2 seconds

Two problems with this:

- *2.5 GB/s fibers have been invented, but where would the data go?*
- *Most of these simple inelastic proton+proton collisions are <u>not interesting</u>!*
  We are looking for rare processes with cross-section: $\boldsymbol{\sigma_{rare}}$

What IS interesting in $p+p$?

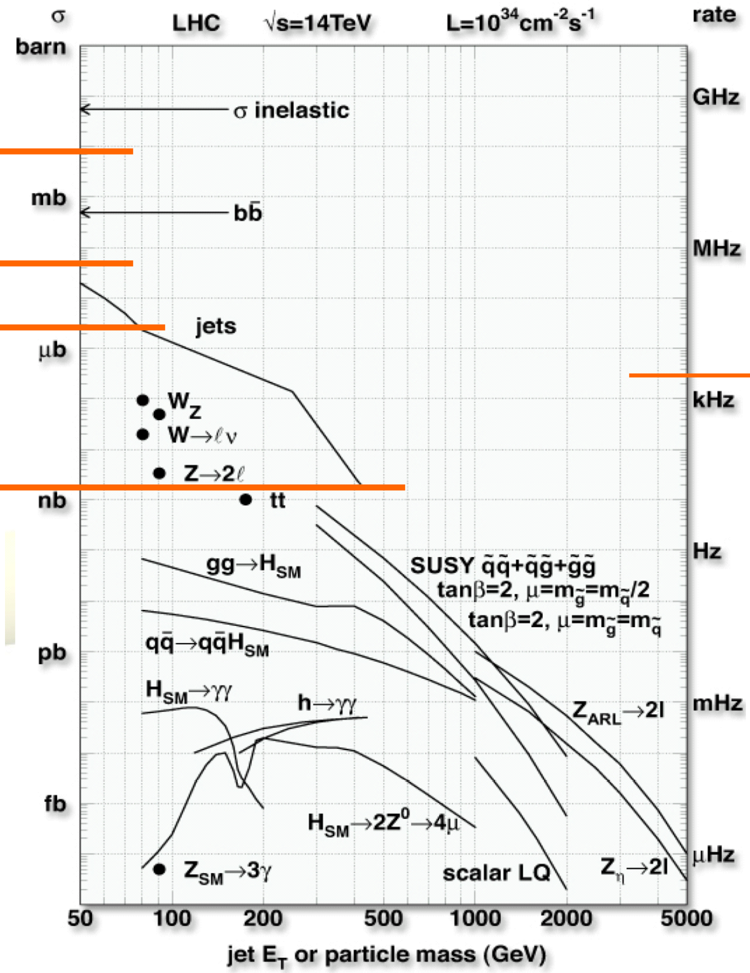
cross-section σ x L = Rate

Studied for over 60 years since proton discovery

Studied at Fermilab (CDF) and SLAC

Important background for LHC physics

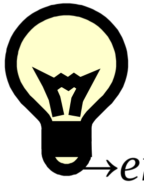
New Discoveries



Max managable DAQ rate at current technology

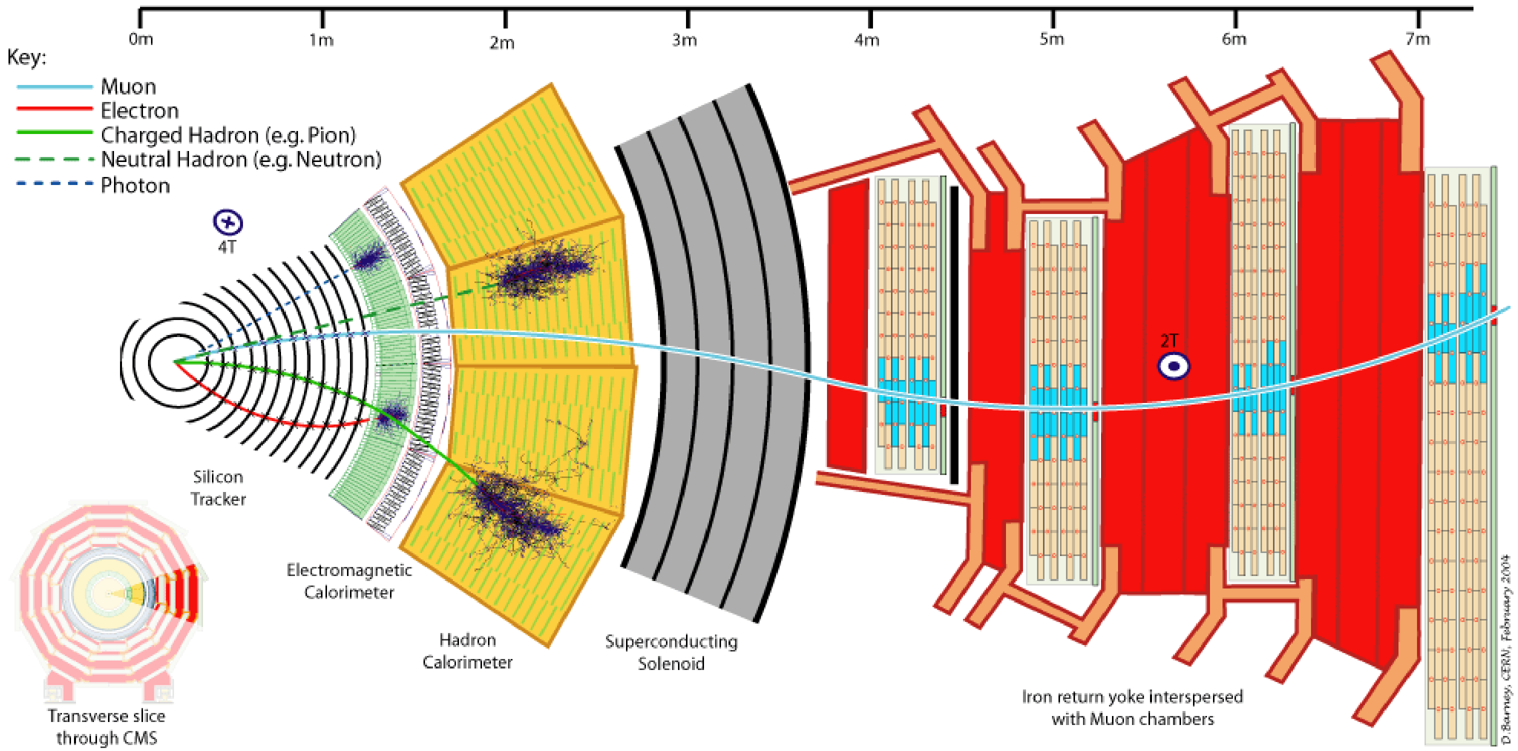
How do you filter the interesting part out ?

IN REAL TIME?



Modern particle physics detectors work on LOGIC:

particle goes through detector material→deposits energy →energy converted to electric signal→digitized→Many detector layers correlated



What does 'Triggering' on Collisions mean?

Trigger ⟶ Your DAQ realizes that a collision has occurred

T=B·L

B is beam-crossing sync signal from LHC control room

L is some user-determined logic

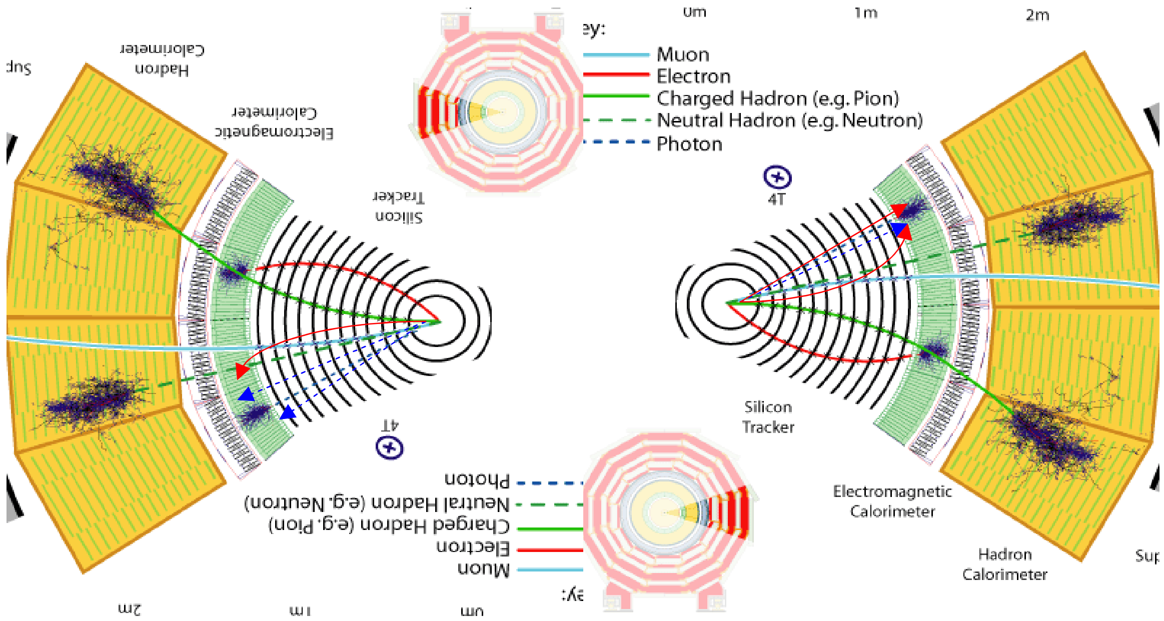
T_0

<u>'minimum bias'</u>

beam and

two back-to-back jets

i.e. many γ,$e^{\pm}$ hits close to each other in EMCal

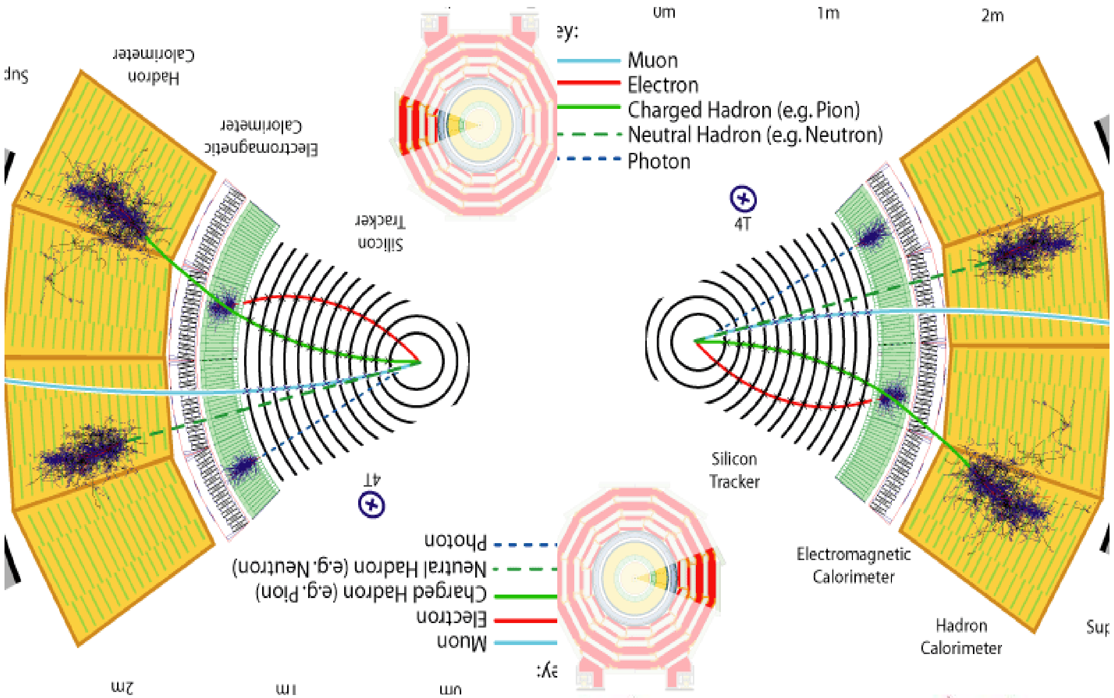


All min-bias events written to disk for later analysis

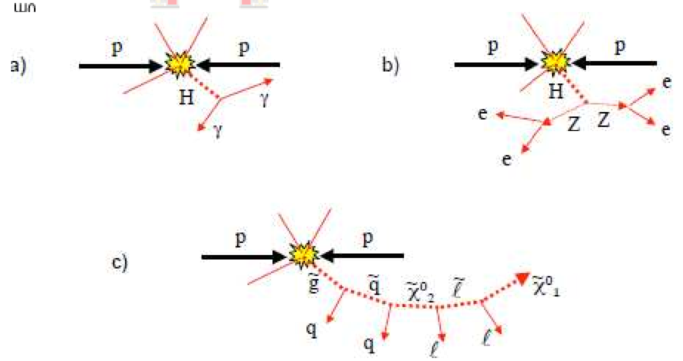
Use Higher Levels of Triggering if you know what to to expect

T_1 T_2 based on signatures of physics processes
a) of interest
b) can be analyzed and tagged in real time to reduce post-analysis.

Big Trade-off is detector Dead-Time
Logic T_1 T_2 takes time



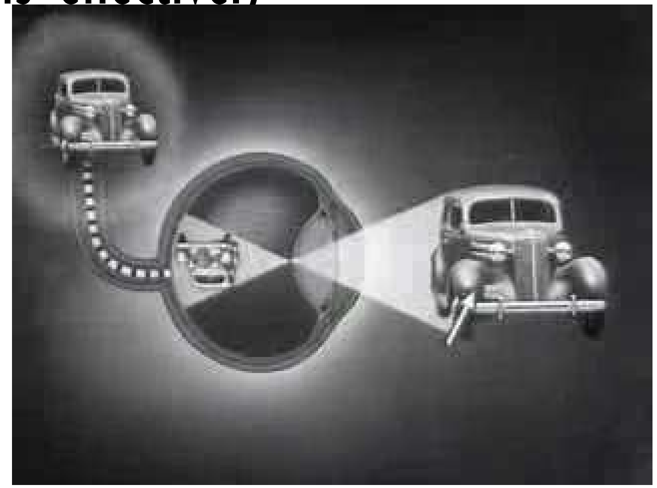
Higgs…SUSY
Two γ,
Two e
back-to-back



Instrumentation is a perpetual struggle against dead time

Recall persistence of vision from Lecture 1– the car image

When your DAQ receives the T_0 signal the detector is effectively 'dead' for a certain amount of time.



The clock starts at collision and signal is deposited in the detector well before the 100ns clock runs out. (probabilistic*)

Main task of parallelized DAQ is to decide T_0 and get the analog electrical signals off the detector elements *before the clock runs out,* else next collision will also deposit it's signal in the same event.

**See William Leo pp 113-118 for a technical discussion & calculation of dead-time*

What are the issues in designing a Detector for LHC?

TIME

1. $p+p$ collision, clock starts ticking for 100 ns.
2. Particles emitted are moving at $\beta \sim c$, so they go through layers of detector nearly instantaneously
3. Energy deposition in the detector material is also very quick *(~ 10's of ps)*
4. The deposited energy has to be converted to electrical charge,
5. Signal must be readout by some analog readout - the digitization is typically massively parallelized and pipelined using FPGA's.

PLACEMENT

1. Each particle has a limited range it can travel in matter before it's completely absorbed/decays. For example, γ and $e^{\pm}$ have a short range.
2. So EM calorimeter must be placed very forward. Other detector types must also be placed accordingly and have enough granularity to give sufficient resolution within space, data, budget constraints

Design Detectors within these constraints

Roughly detector types fall into categories:

- Gas detectors
- Solid-State Detectors

} Charged particle detectors that rely on ionization energy loss - Bethe-Bloch!

- Calorimeters (Electromagnetic and Hadronic)
- Čerenkov and Transition Radiation

Systems Approach: Each detector comes with it's associated readout
We have to consider the performance of the system.

What is the Basic Principle?

ALL Detectors are based on registration of energy loss.
(Bethe-Bloch): particles going through detector lose energy by interacting with e^-
Do they lose enough energy to ionize the e^- into a free state?

GAS Detectors

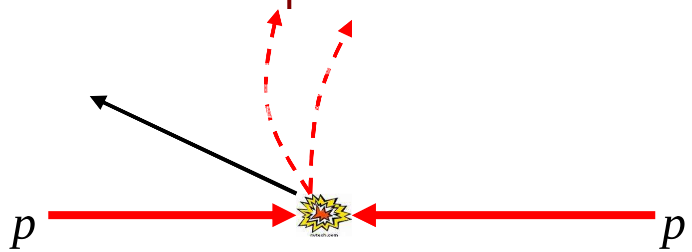
MWPC, Drift Chambers. TPC, GEM, MPGC…

Charged particle leaves a trail of electron-ion pairs in it's path

Solid-State Detectors

Silicon, Germanium…

Charged particle leaves a trail of electron-hole pairs in it's path



Calculate the Ionization charge for a MIP passing through two detectors

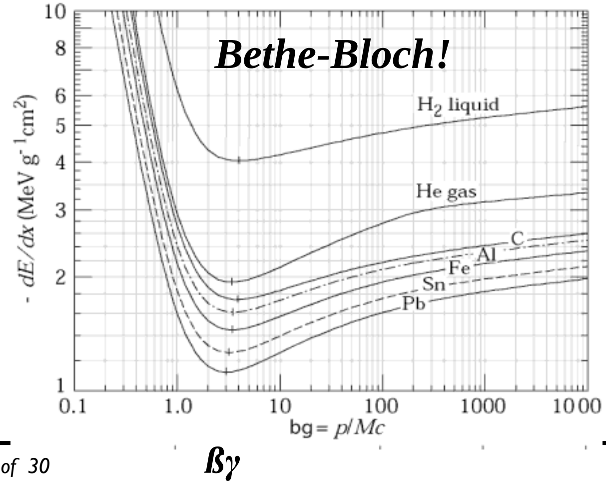
1 cm | *1 cm*

Charged particle goes through 1cm of gas, and 200 μm Ge

Energy loss for MIP determined by Z/A

Ar gas	*Si/Ge Solid State*
$dE/dx|_{MIP} \sim 1.52\ MeVg^{-1}cm^2$	$dE/dx|_{MIP} \sim 1.39\ MeVg^{-1}cm^2$
$I_o = 26\ eV$	$I_o = 2.9\ eV$ density ~ 1000 x gas
so ~ 100 e^--ion/cm	so ~ 10^6 e-h pairs/cm

Forget it!
Lost in kT thermal noise



~ 100 fC of charge amplifiable

Why is it hard to amplify 100 e$^-$-ion pairs?

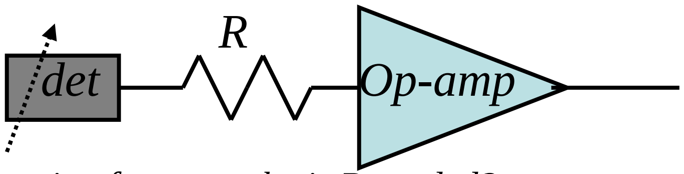
Some basic electronics:

All electronic amplification introduces noise.

Small detector signal can get lost in the amplification noise.

I – Thermal Noise due to the load resistance

$R \sim M\Omega$



Question for you: why is R needed?

$$\bar{v}_{th} = \sqrt{k_b T R \Delta f}$$

$V_{th} \sim 4\ nV/\sqrt{Hz}$

$$\bar{i}_{th} = \sqrt{\frac{k_b T \Delta f}{R}}$$

$i_{th} \sim 4\ fA/\sqrt{Hz}$

For details see the web – tutorials from Analog Devices and Texas Instruments at:

a) *http://www.analog.com/static/imported-files/tutorials/MT-047.pdf*

b) *http://focus.ti.com/lit/ml/sloa082/sloa082.pdf*

How is the amplifier noise quantified?

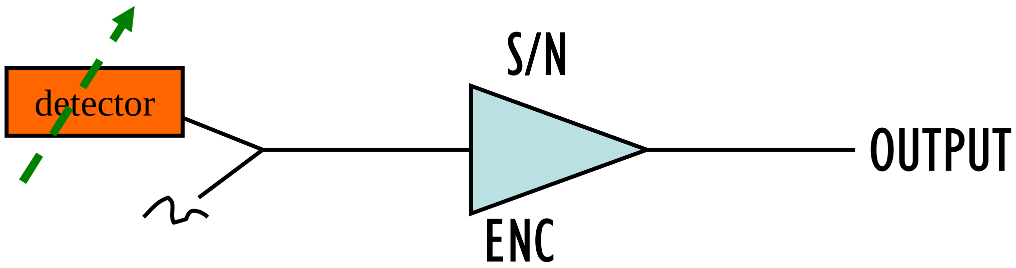
The deposited charge must be amplified and readout by dedicated electronics.

The amplification needed depends on the Signal (S). Amplifiers also have noise (N)

We want S/N >> 1

The noise is characterized by the 'Equivalent Noise Charge (ENC)'

ENC = Charge at the input that produces an output signal equal to the noise.



Gas v/s Solid-state detectors

- Typical ENC numbers of best amplifiers are ~ $1000e^-$.

- So the registered charge must be much higher than the ENC of the amplifier.

→ constraint on the detector is deposited q >> 1000 e^-

- Gas Detector: $q=80e^-$ /cm → too small.

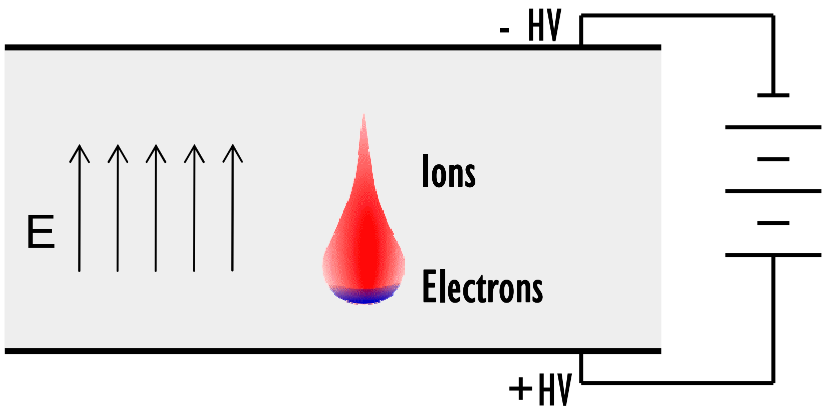
  Solid State detectors with 10^6/cm OK! (for charge deposition)

To be useful…

Gas detectors need <u>internal amplification</u> to be sensitive to single particle tracks, or need many particles to pass through the detector at once (ionization detectors)

How does internal amplification work?

Basic principle: At sufficiently high electric fields (~ 100 kV/cm) electrons moving through a gas gain energy *in excess* of the ionization energy for the gas



$$dN = N\alpha\, dx \quad (\alpha \text{ is the Townsend co-efficient})$$

$$N(x) = N_0 e^{\alpha x}$$

$$\frac{N}{N_0} = A \text{ is the Gas Gain (amplification factor)}$$

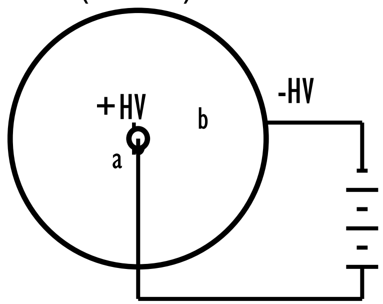
In general, α is determined by gas mixture and E field config

Gas Detectors – "we were the best" (1950-70's)

GEOMETRY 1- WIRE CHAMBERS

A fine conductive wire (radius ~ 10-25μm) strung trhrough t a tube of radius b (1-3cm):

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r} = \frac{V_0}{\ln\frac{b}{a}}\frac{1}{r}, \qquad V(r) = \frac{V_0}{\ln\frac{b}{a}}\ln\frac{r}{a},$$

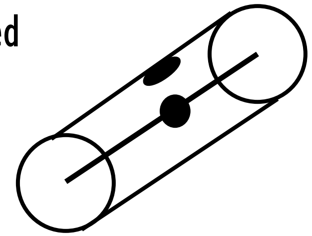


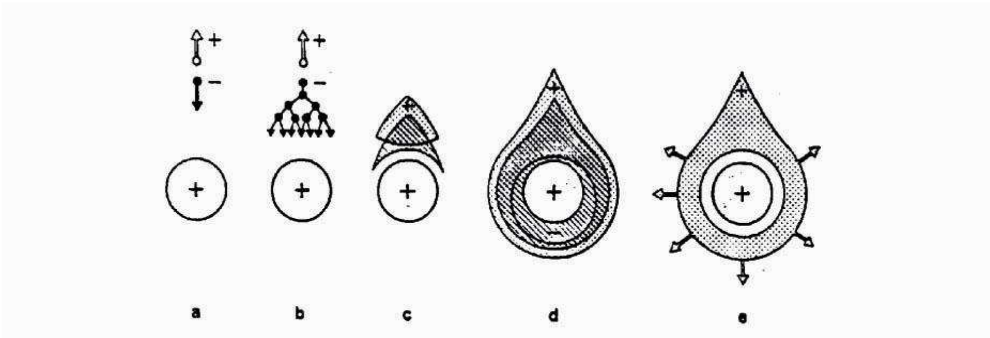
Electric field close to a thin wire (100-300kV/cm). E.g. V_0=1000V, a=10μm, b=10mm, E(a)=150kV/cm

Electric field high enough to accelerate electrons to energies which are sufficient to produce secondary ionization → electron avalanche

→Signal amplified

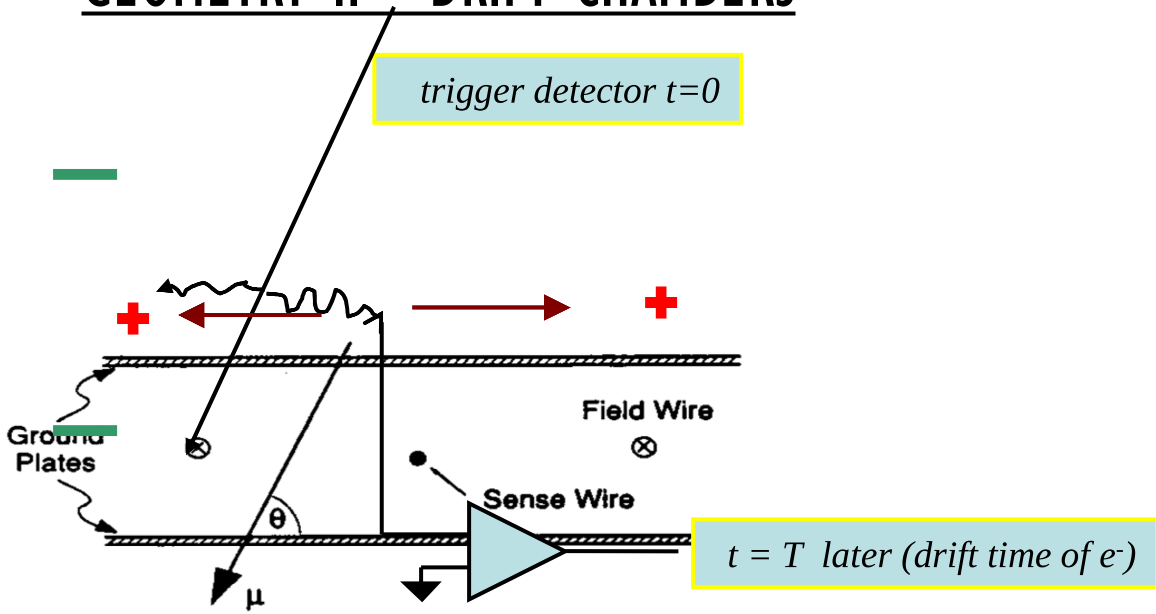
→Mission accomplished





Gas Detectors – "Then we got better" (1970's-)

GEOMETRY II - DRIFT CHAMBERS

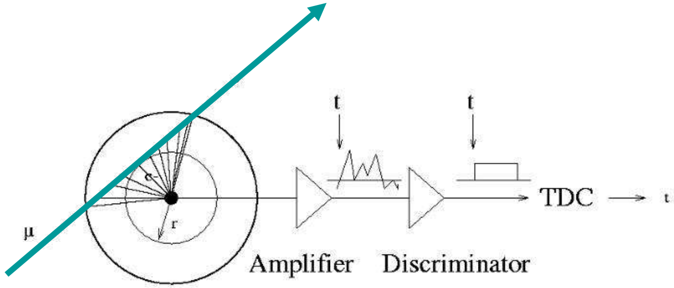


- e⁻ are light, Ions heavy, so they drift at different speeds in gases
- Use time of arrival of amplified signal for precise position determination.
- Reduce number of field wires required in the bargain.

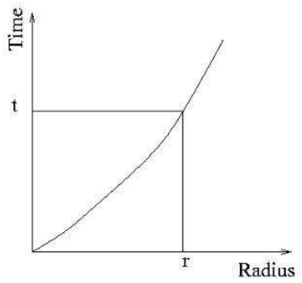
Gas detectors still very much alive today

Used in ATLAS @ LHC on large scale

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation



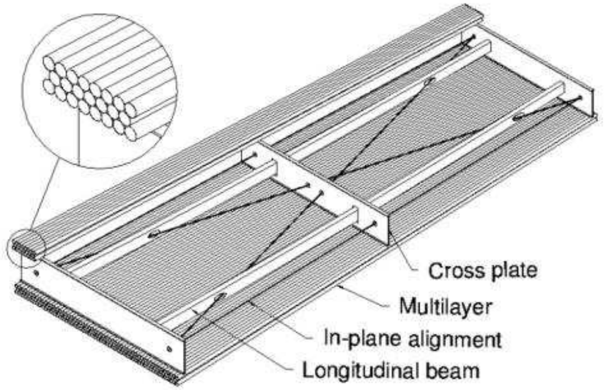
Primary electrons are drifting to the wire.

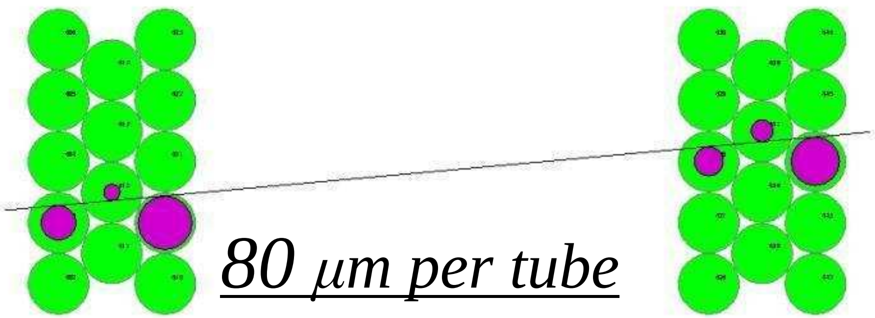
Electron avalanche at the wire.

The measured drift time is converted to a radius by a (calibrated) radius-time correlation.

Many of these circles define the particle track.

ATLAS Muon Chambers





ATLAS muon drift detector ~ Ferrari of detector world

Atlas Muon Spectrometer, 44m long, from r=5 to 11m.

1200 Chambers

6 layers of 3cm tubes per chamber.

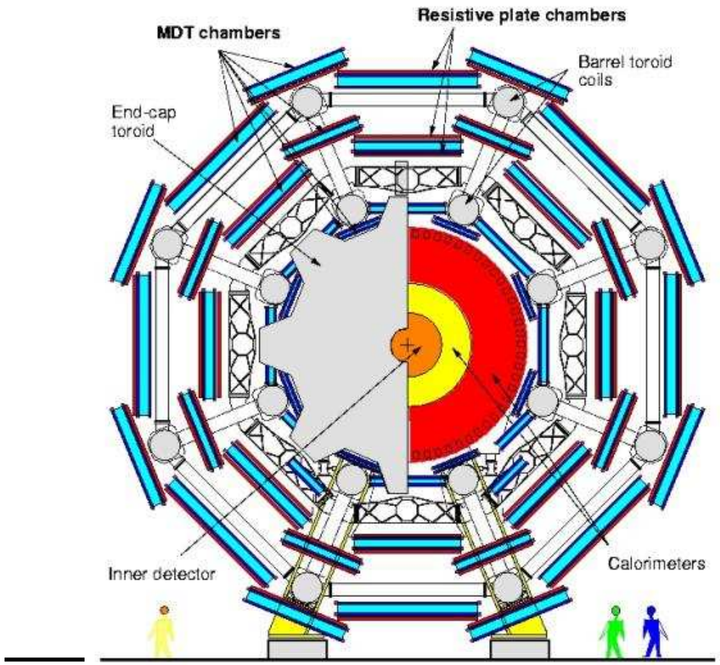
Length of the chambers 1-6m !

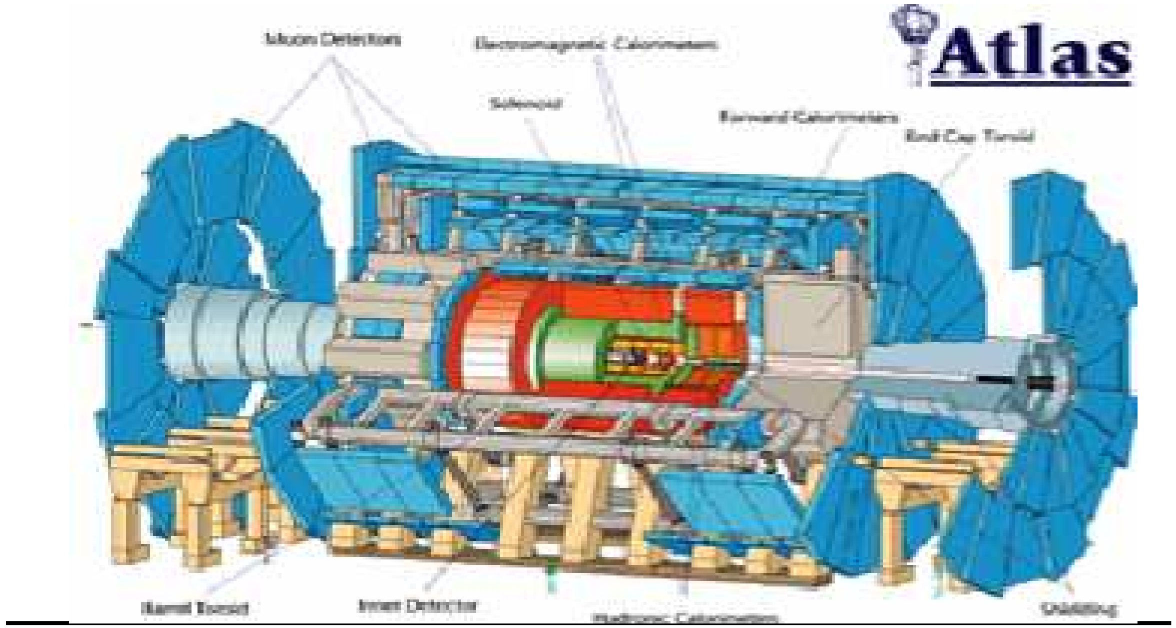
Position resolution: 80μm/tube,

< 50μm/chamber (3 bar)

Maximum drift time ≈70ns

Gas Ar/CO_2 93/7





The supreme advantage of Gas detectors

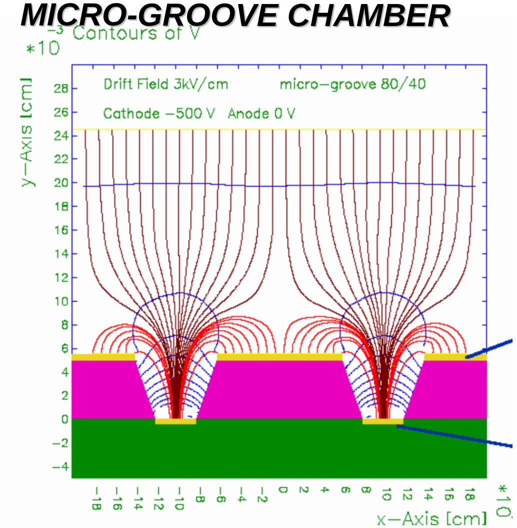
Gas avalanche detectors put minimal material in the path of charged particles
$\longrightarrow$ cause minimal effect on the particle's properties

The particle goes through large volume of low-density gas – leaves signal through small energy deposition in a low-density medium ($dE/dx \sim MeVg^{-1}cm^2$)

Yet by correlating the timing of the signals, you can track the particle's path in a B field $\rightarrow$ measure it's momentum

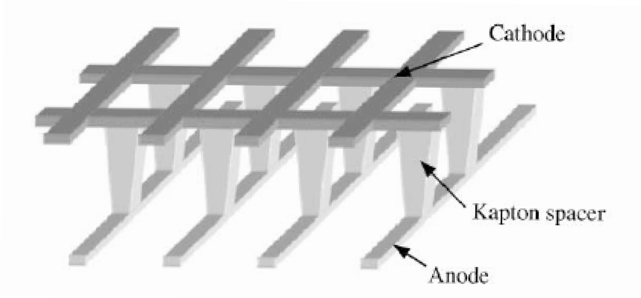
New tecnology in Gas detectors

MICRO-GROOVE CHAMBER



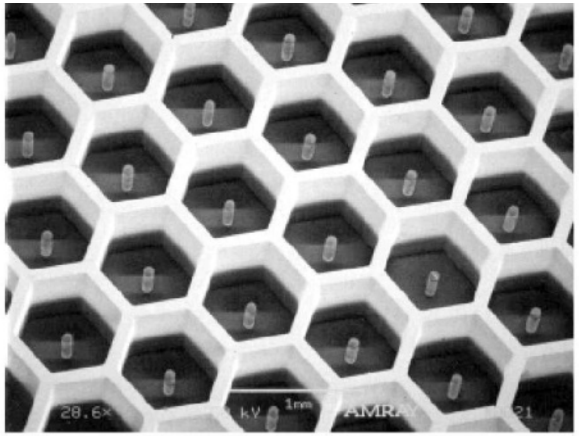
Bellazzini et al NIMA424(99)444

MICROWIRE CHAMBER



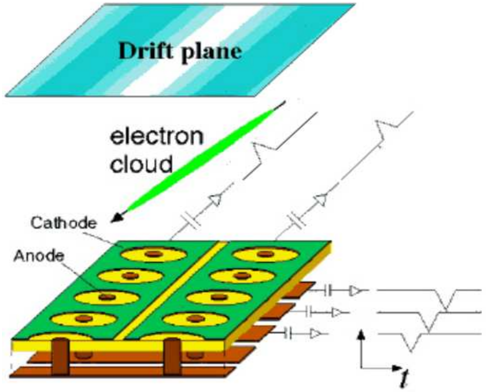
B. Adeva et al NIMA461(2001)33

MICRO-PIN ARRAY (MIPA)



P. Rehak et al TNS NS47(2000)1426

MICRO-PIXEL CHAMBER

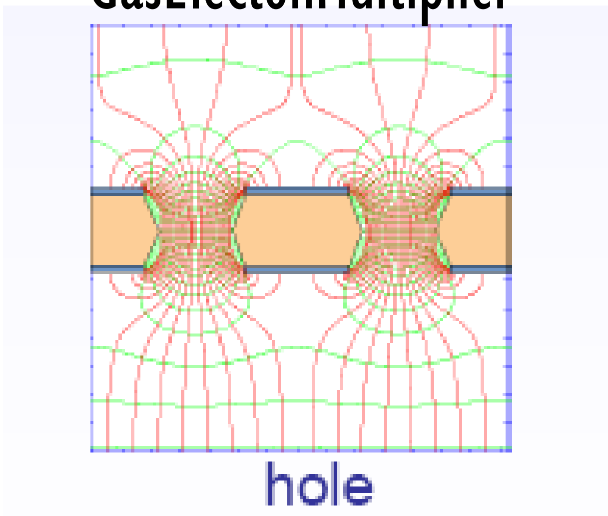


Ochi et al NIMA471(2001)264

Winning technologies

GEM

GasElectonMultiplier



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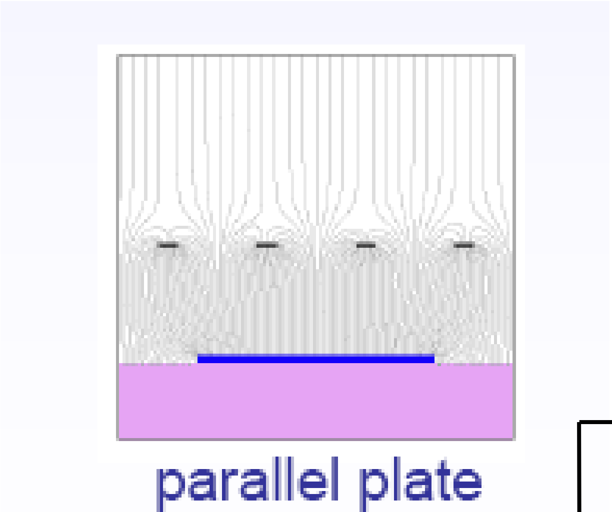
MICROMEGAS

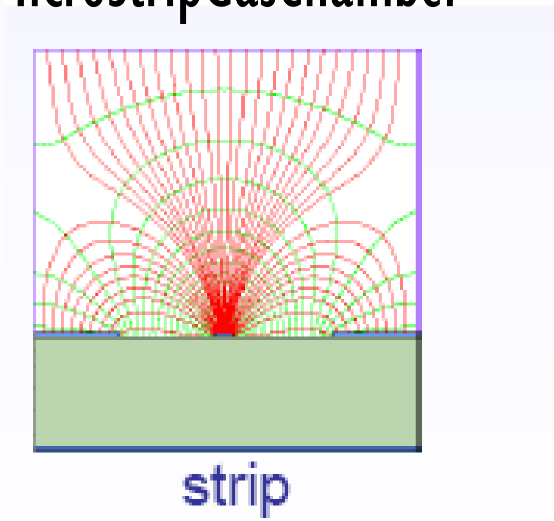
MicroMeshGas



2

MSGC

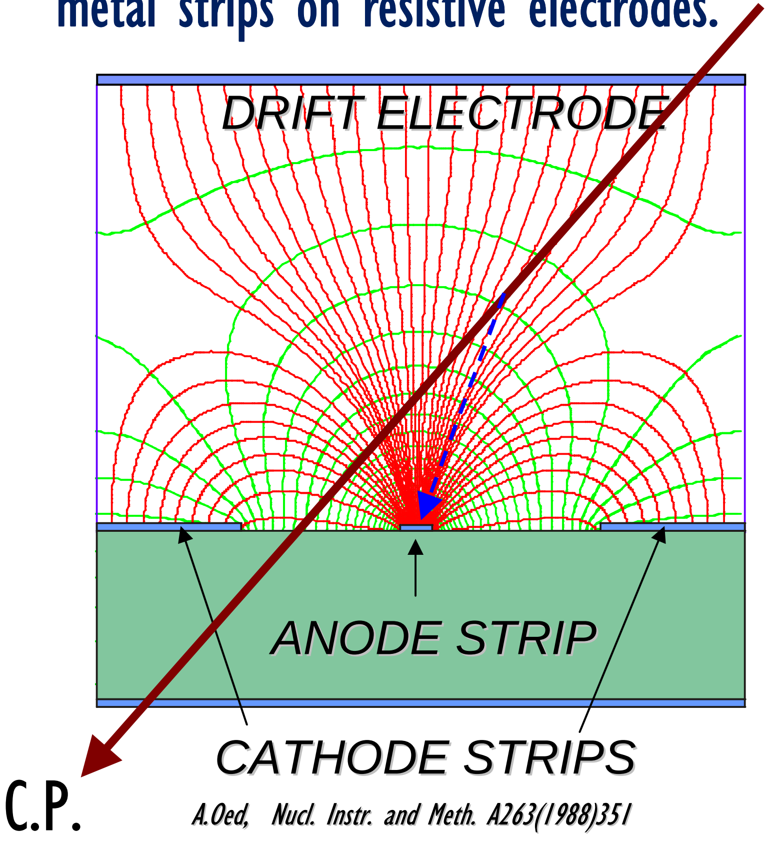
MicroStripGasChamber



3

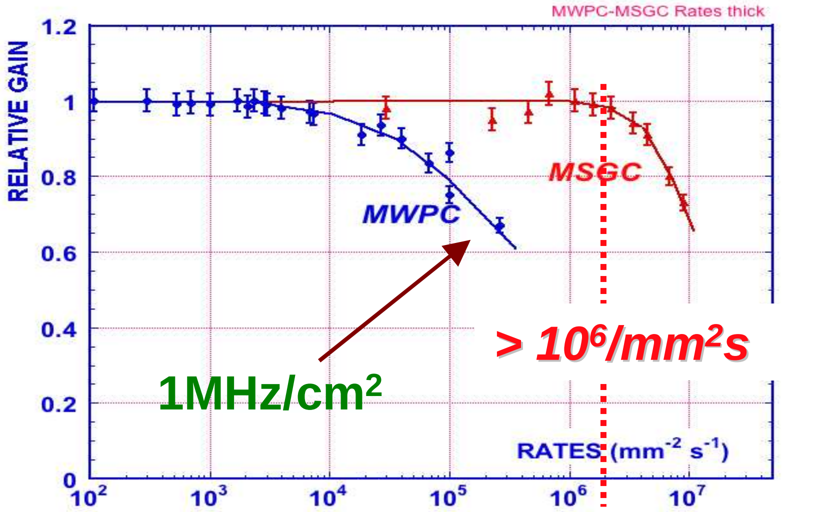
MSGC – High rate, but spark issues

Gas gain is provided not by wires but by metal strips on resistive electrodes.

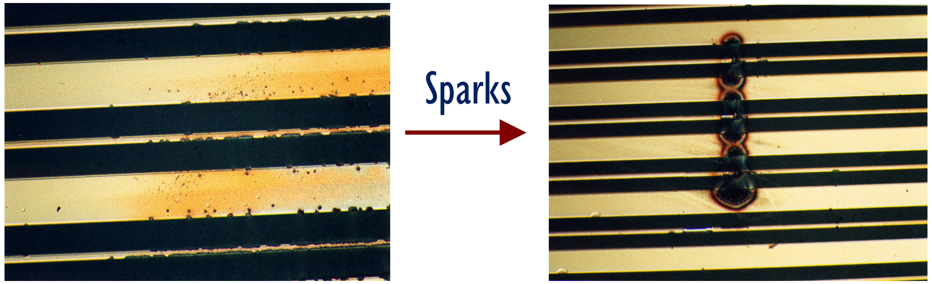


A.Oed, Nucl. Instr. and Meth. A263(1988)351

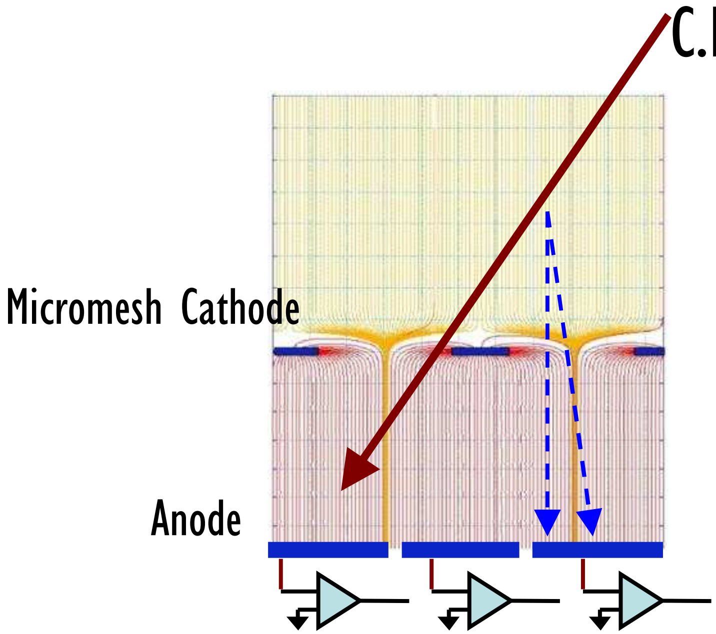
Due to small pitch and fast charge collection MSGCs have very high rate capability.

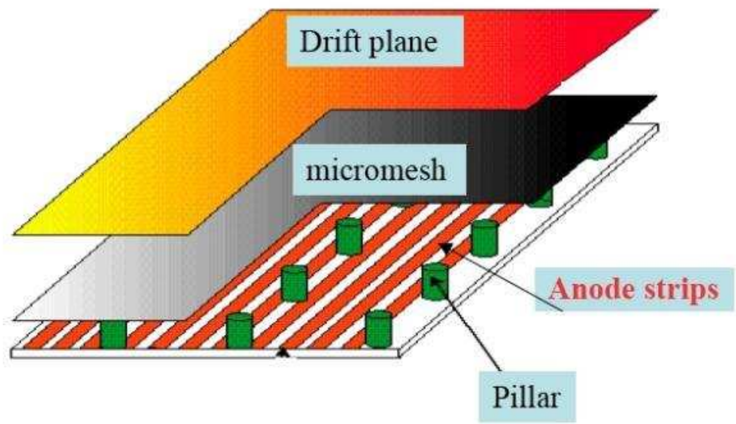


R. Bouclier et al, Nucl. Instr. and Meth. A323(1992)240



MICROMEGAS





Y. Giomataris et al, Nucl. Instr. and Meth. A376(1996)239

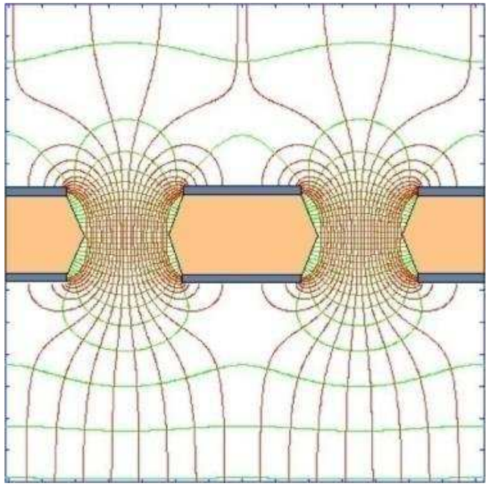
- 👌 Raise one electrode to a higher plane – increase separation
- 👍 Reduce feature size: avalanche develops over distance ~ 100 μm
  - ⇨ very fast response ~ 200 MHz readout capable
- 👎 Sharp edges of electrodes ⇨electric field complex, sparks still possible

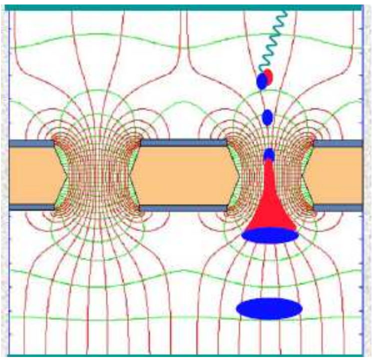
  Recharge time 'dead time' of readout increased, damage less likely

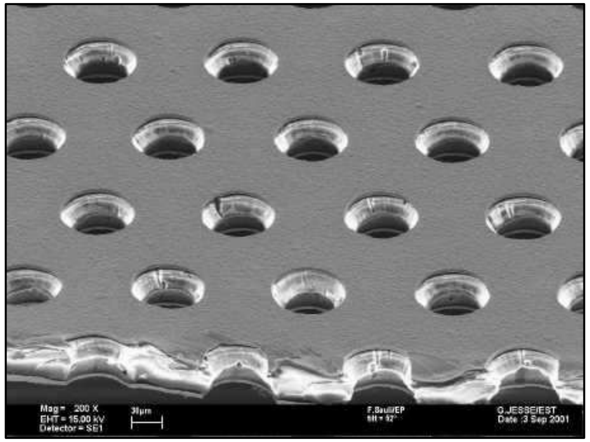
GasElectonMultiplier (GEM) detectors

Thin metal-coated polymer foils

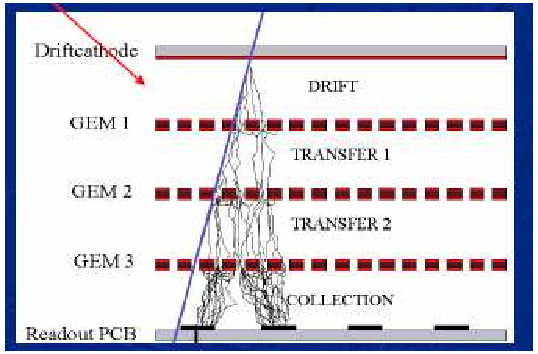
70 μm holes at 140 mm pitch





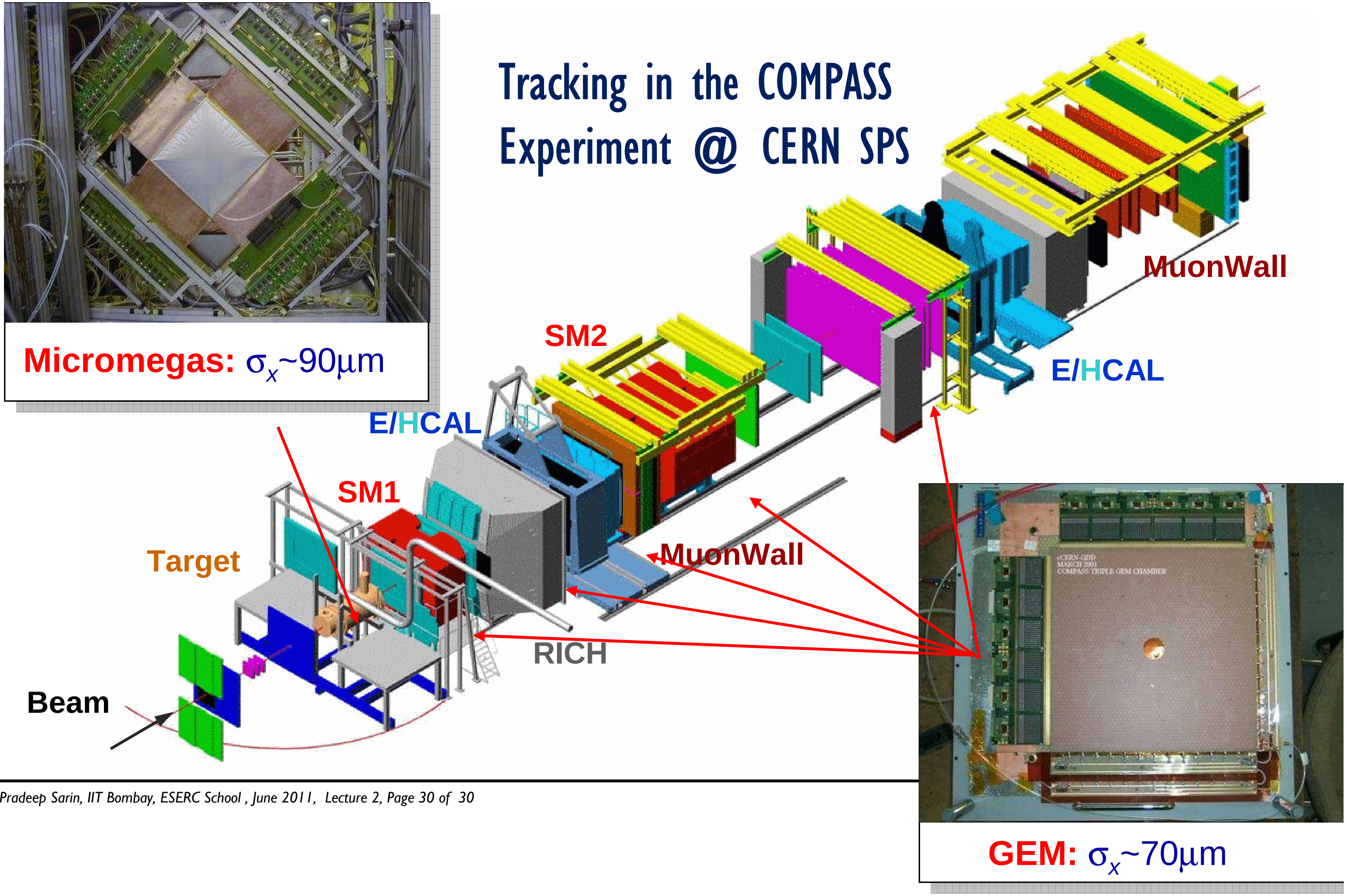


F. Sauli, Nucl. Instr. and Methods A386(1997)531



Typically cascaded to reduce gain/stage & avoid sparking

First large scale use of GEM



Summary

Today:

- Detector Systems Design issues

- Overview of gas avalanche detectors
  and new technology: MSGC, MICROMEGAS, GEM

<u>Next:</u> Solid-state detectors