Physics of Particle Detectors

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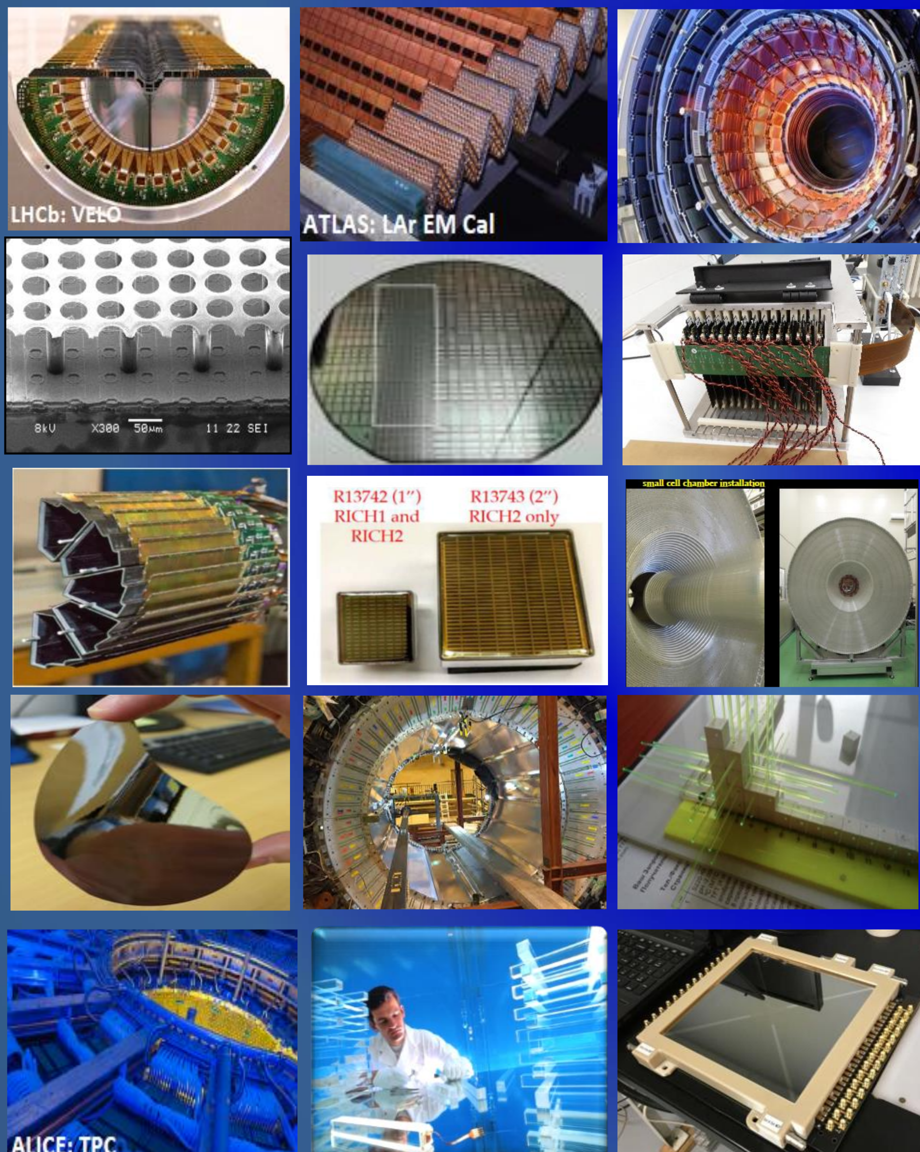

- Introduction and Overview
- Particle Interactions with Matter
- Advancing Concepts Tracking Detectors (Gaseous & Silicon Detectors)
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing
- Summary and outlook

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Georg-August-Universität Göttingen
Göttingen, Germany, Jul. 28 – Aug.5, 2024

The History of Instrumentation is VERY Entertaining

- ✓ A look at the history of instrumentation in particle physics

  → complementary view on the history of particle physics, which is traditionally told from a theoretical point of view

- ✓ The importance and recognition of inventions in the field of instrumentation is proven by the fact that

  → several Nobel Prices in physics were awarded mainly or exclusively for the development of detection technologies

Nobel Prizes in instrumentation ("tracking concepts"):

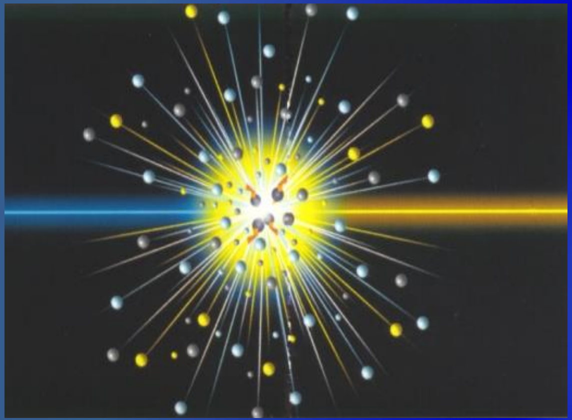
- ❖ 1927: C.T.R. Wilson, Cloud Chamber
- ❖ 1960: Donald Glaser, Bubble Chamber
- ❖ 1992: Georges Charpak, Multi-Wire Proportional Chamber

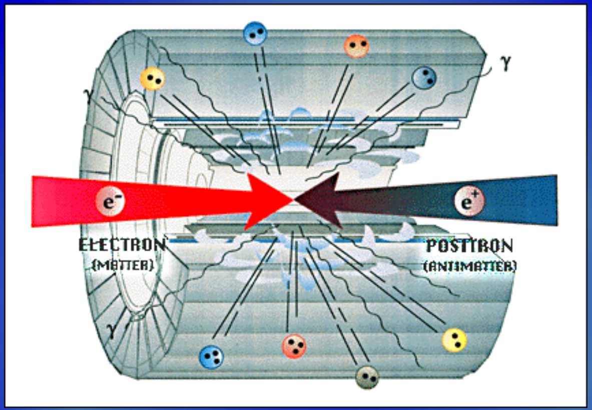
Tools of the Trade → Particle Accelerator

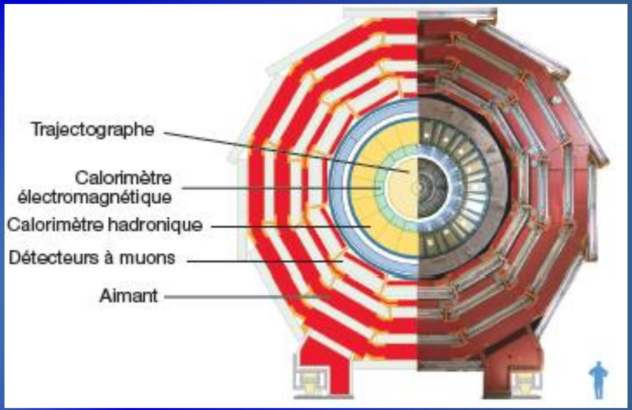
Collision of accelerated particles → "Grain" of energy → New Particles

High energies are needed to produce massive particles & look into smaller distances E ~ 1/λ

Accelerators | **$E = mc^2$** | **Detectors**



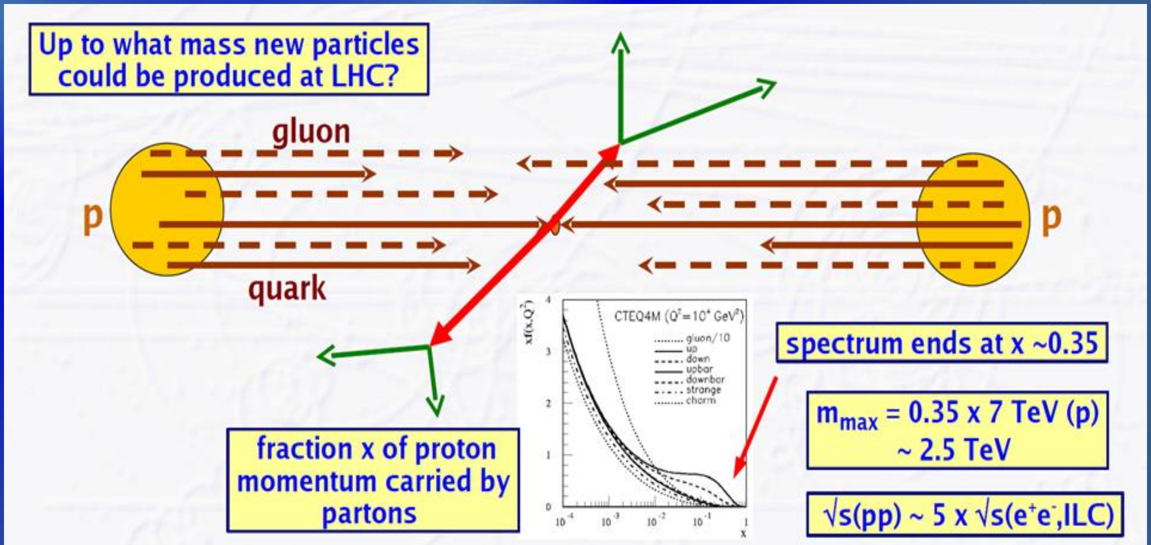




Power of resolution:

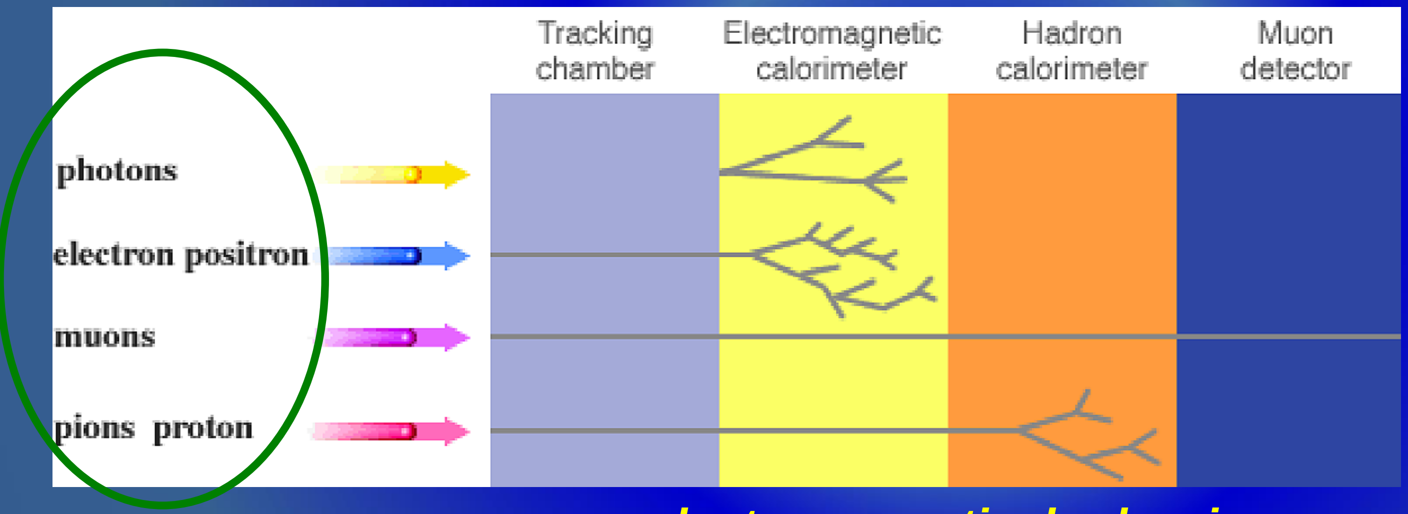
$$\lambda(m) = 1.24\ 10^{-15} / P(GeV/c)$$

LHC (14TeV) → 9×10^{-17} m



Schematic View of a Particle Collider Detectors

- *There is not one type of detector which provides all measurements we need -> "Onion" concept -> different systems taking care of certain measurement*
- Detection of collision production within the detector volume
  - → resulting in signals due to electro-magnetic interaction
  - → exceptions: strong interactions in hadronic showers (hadron calorimeters)
  - → weak interactions at neutrino detection (not discussed here)



undetected ***neutrinos...***

electromagnetic hadronic
showers

momentum *measurement by curvature in magnetic field*

energy *measurement by creation and total absorption of showers*

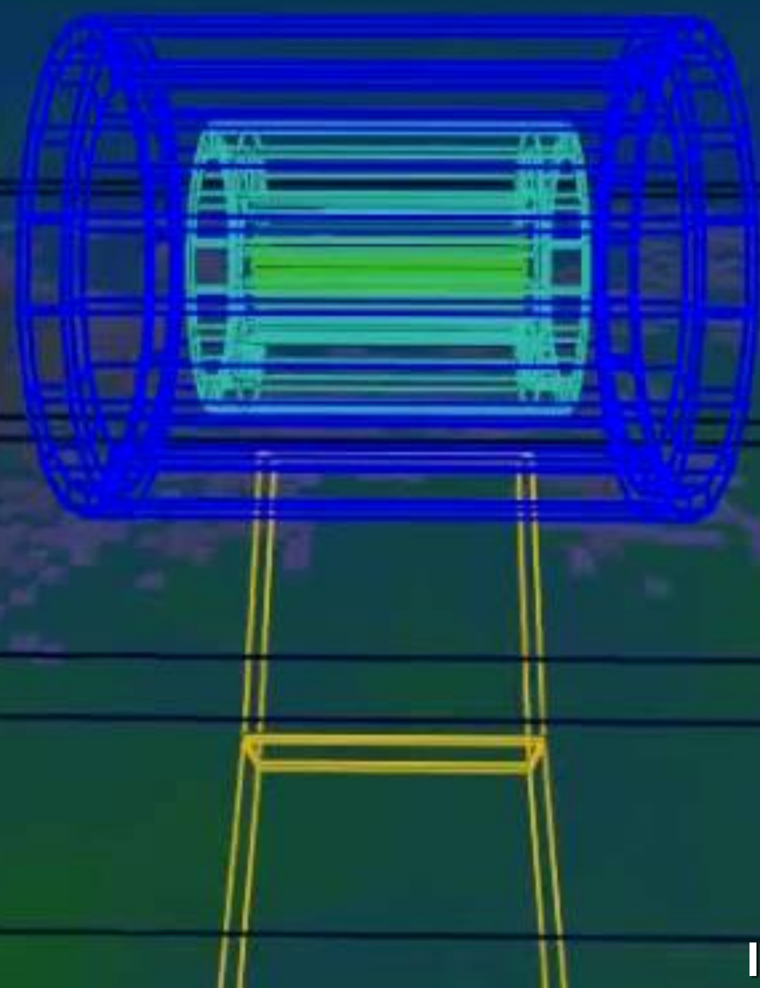
muon detection with improved momentum measurement (long lever arm)

Particle Detectors: Basic Physics Principles

- **Tracking Detector (or Tracker) = momentum measurement**
  - closest to interaction point: vertex detector (often silicon pixels)
    - measures primary interaction vertex and secondary vertices from decay particles
  - main or central tracking detector
    - measures momentum by curvature in magnetic field
    - two technologies: solid state (silicon) detectors or gaseous detectors
- **Calorimeters = energy measurement**
  - electro-magnetic calorimeters
    - measures energy of light EM particles (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production
    - Two concepts: homogeneous (CMS) or sampling (ATLAS)
  - hadron calorimeters
    - measures energy of heavy (hadronic) particles (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions
- **Muon Detectors = momentum measurement for muons**
  - outermost detector layer, basically a tracking detector

> 2010: a New Era in Fundamental Science

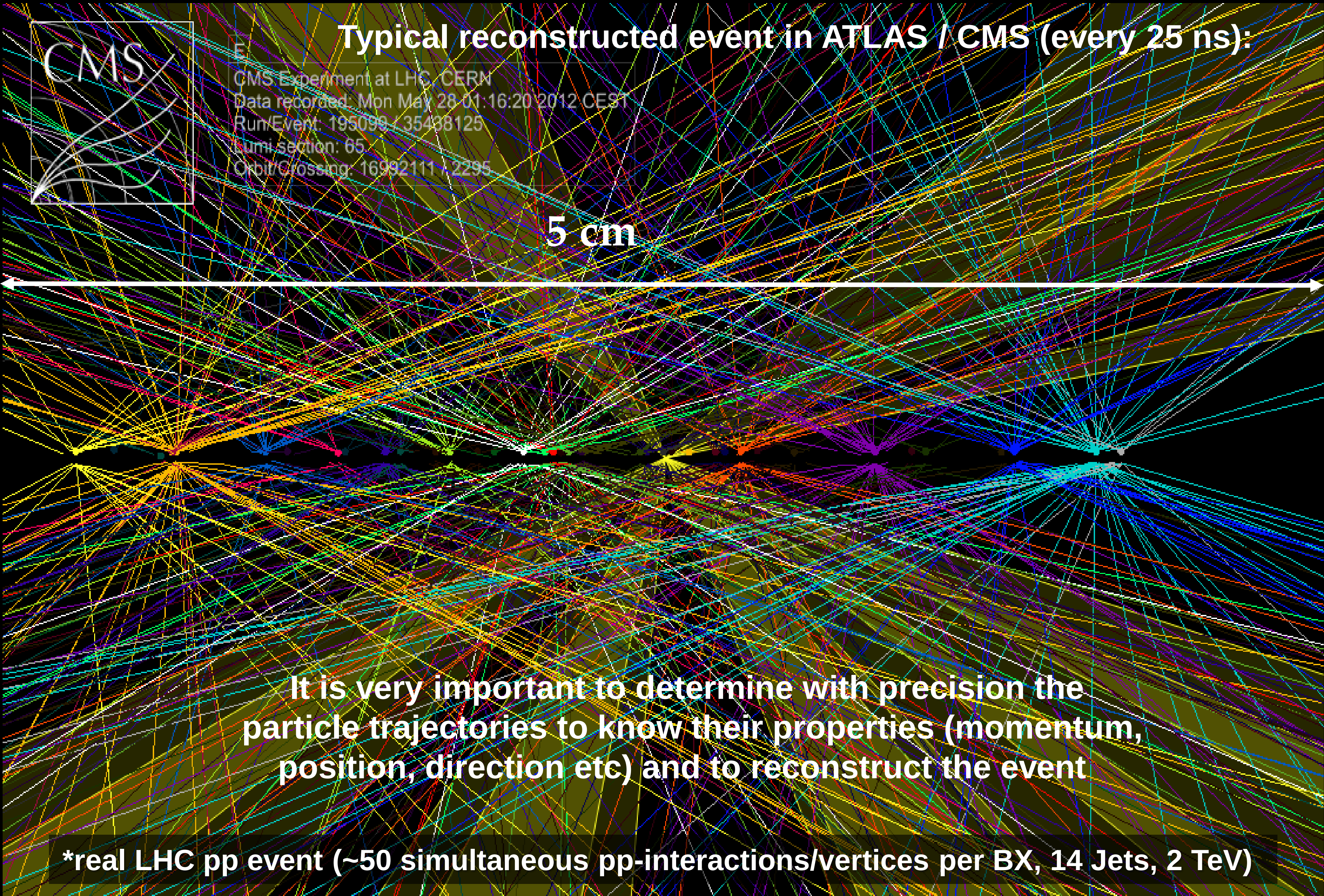
LARGE HADRON COLLIDER SIMULATION: Increasing Multiplicities and Challenges In Collider Experiments



Particle	Life Time τ	$c \cdot \tau$
γ	∞	∞
e^-	∞	∞
ν	∞	∞
p^+	>1.6 10^{33} y	∞
n	887 s	2.7 10^{8} km
μ^-	2.2 10^{-6} s	659 m
π^+	2.6 10^{-8} s	7.8 m
K^+	1.2 10^{-8} s	3.7 m
K^0_L	5.2 10^{-8} s	15.5 m
K^0_S	0.9 10^{-10} s	2.7 cm
$\Lambda^0 \Sigma^+ \Xi^0 \Omega^- \ldots$	~10^{-10} s	~3 cm
$D^{0+} B^{0+} \Lambda_c^+ \Lambda_b^0$	~10^{-12} s	~300 μm
π^0	8.4 10^{-17} s	25 nm
$\eta\ \psi \ldots$	<10^{-19} s	–

In practice we detect only:

What do We See in Reality – The Challenge of Pileup

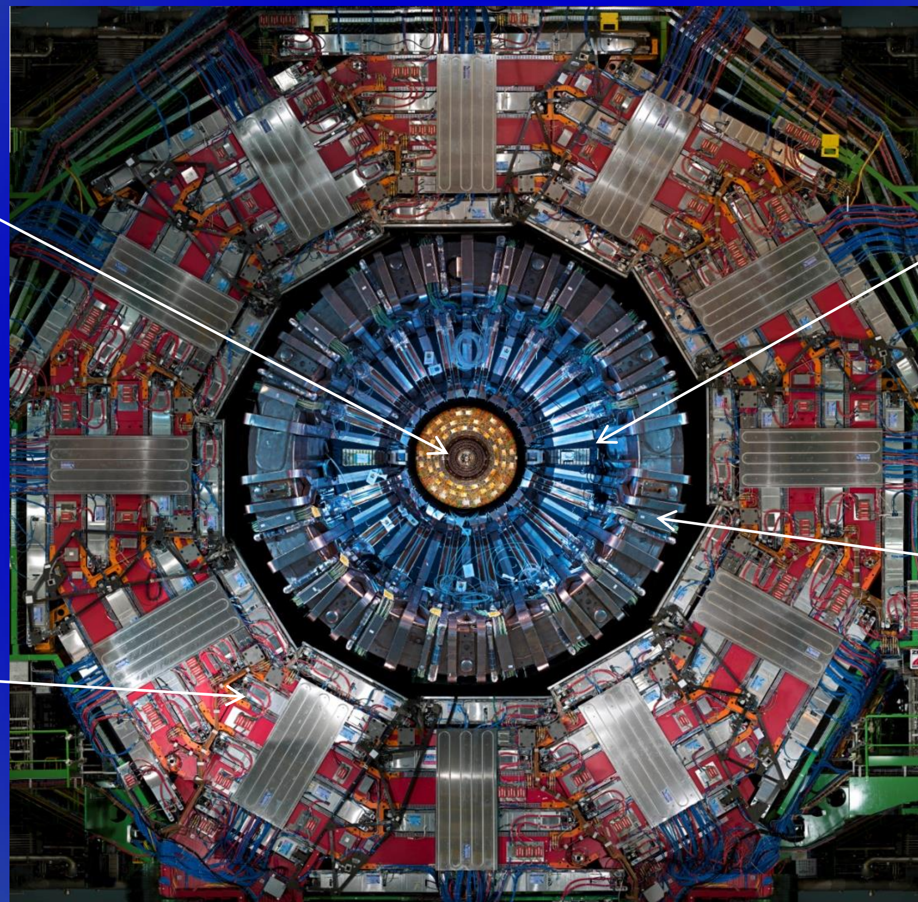


The CMS Detector: Concept to Data Taking – Took 18 Years

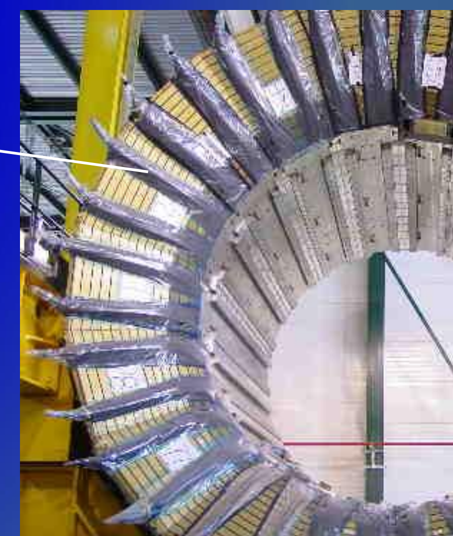
3000 scientists from 40 countries
CMS Letter of Intent (Oct. 1992)

Silicon Tracker

Gaseous detectors



Scintillating Crystals



Brass plastic scintillator

Need to make very <u>advanced systems:</u>
Forefront of: Engineering, Imaging Sensors, Electronics, Computing

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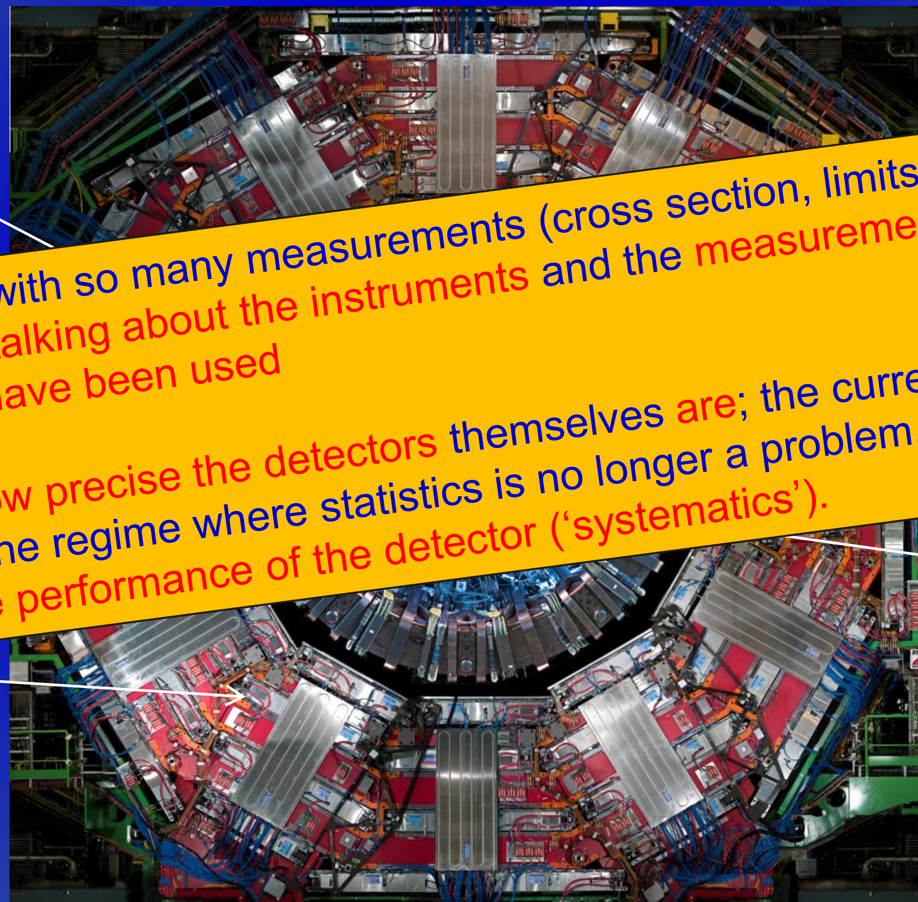
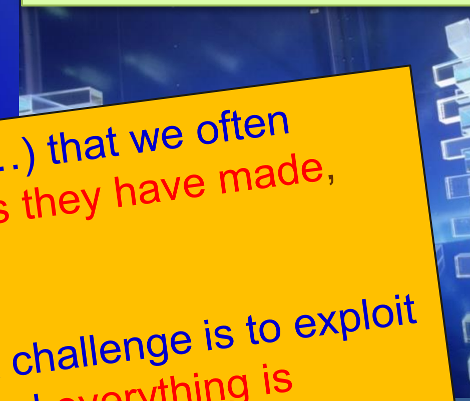


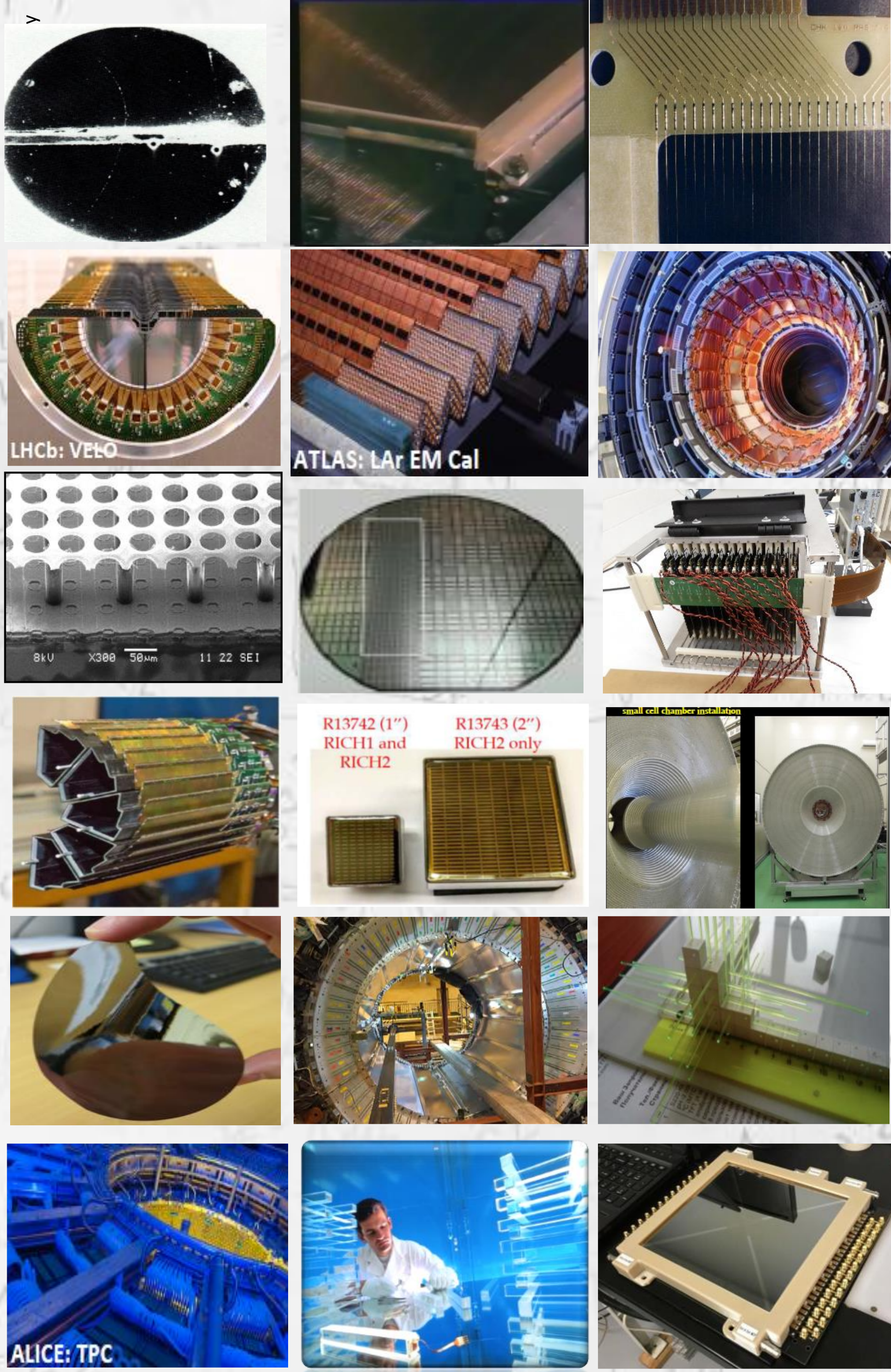


- ✓ We are presented with so many measurements (cross section, limits, …) that we often forget that we are talking about the instruments and the measurements they have made, and the methods have been used
- ✓ The surprise is how precise the detectors themselves are; the current challenge is to exploit that precision in the regime where statistics is no longer a problem, and everything is dominated by the performance of the detector ('systematics').

Gaseous detectors

Need to make very <u>advanced systems:</u>
Forefront of: Engineering, Imaging Sensors, Electronics, Computing

Brass plastic scintillator



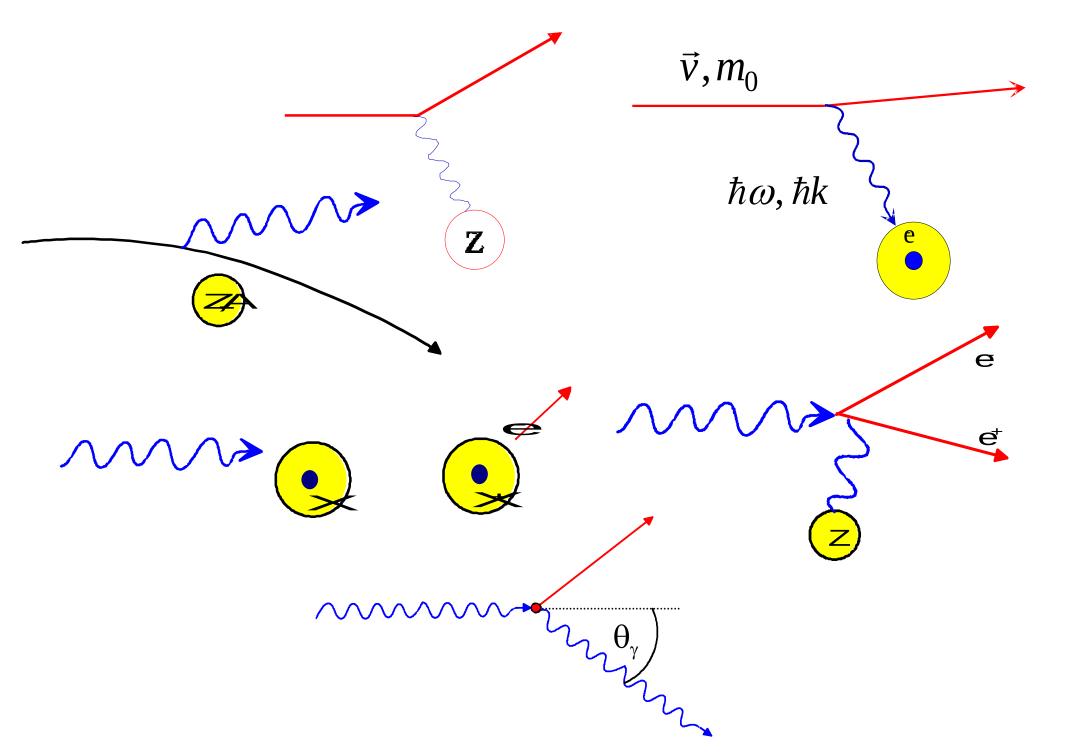
- Particle Interactions with Matter
- "Classic" Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Basics of All Detection Processes: Particle Interactions with Matter

- **Charged Particle Interactions**
  - **Scattering, Ionization**
  - **Photon Emission: Bremstrahlung, Čerenkov & Transition Radiation, Excitation (scintillators)**
- **Photon Interactions**
  - **Photoeffect**
  - **Compton Scattering**
  - **Pair Production**
- **Detection of Neutrons**
  - **Strong Interactions**
- **Detection of Neutrinos**
  - **Weak Interactions**

✓ *If the particle is to pass through essentially undeviated, this interaction must be a soft electromagnetic one.*

✓ *Otherwise, measure energy loss or total energy from total absorption detectors (Particle ID from gaseous detectors, Cherenkov detectors, Transition Radiation Detectors, Energy Measurement from Calorimetry)*



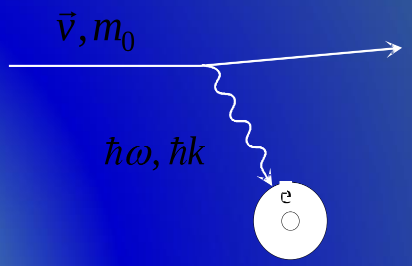
Charge Particle Interactions

- ✓ **(Multiple) elastic scattering with atoms of detector material**

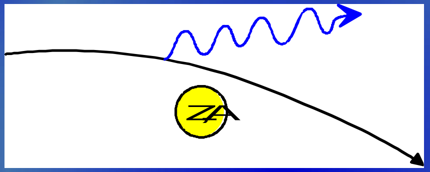
  mostly unwanted, changes initial direction, affects momentum resolution

- ✓ **Ionization**

  the basic mechanism in tracking detectors



- ✓ **Photon radiation**



  - ***Bremsstrahlung***

    initiates electromagnetic shower in calorimeters, unwanted in tracking detectors

  - ***Čerenkov radiation*** *(*Contribute very little to the energy loss < 5%)

    hadronic particle identification

    also in some homogeneous electromagnetic calorimeters (lead glass)

  - ***Transition radiation*** *(*Contribute very little to the energy loss < 5%)

    electron identification in combination with tracking detector

- ✓ **Excitation**

  Creation of scintillation light in calorimeters (plastic scintillators, fibers)

(Heavy) Charge Particle Energy Loss Due to Ionization

Bethe-Bloch formula

Many equivalent parameterizations in the literature

Quantum mechanic calculation of Bohr stopping power

Valid for heavy charged particles ($m_{incident} >> m_e$), e.g. proton, k, π, μ

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2}{I^2} W_{max} \right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right]$$

$= 0.1535$ MeV cm^2/g

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a \beta^2 \gamma^2 \right)$$

Fundamental constants

- r_e = classical radius of electron
- m_e = mass of electron
- N_a = Avogadro's number
- c = speed of light

Absorber medium

- I = mean ionization potential
- Z = atomic number of absorber
- A = atomic weight of absorber
- ρ = density of absorber
- δ = density correction
- C = shell correction

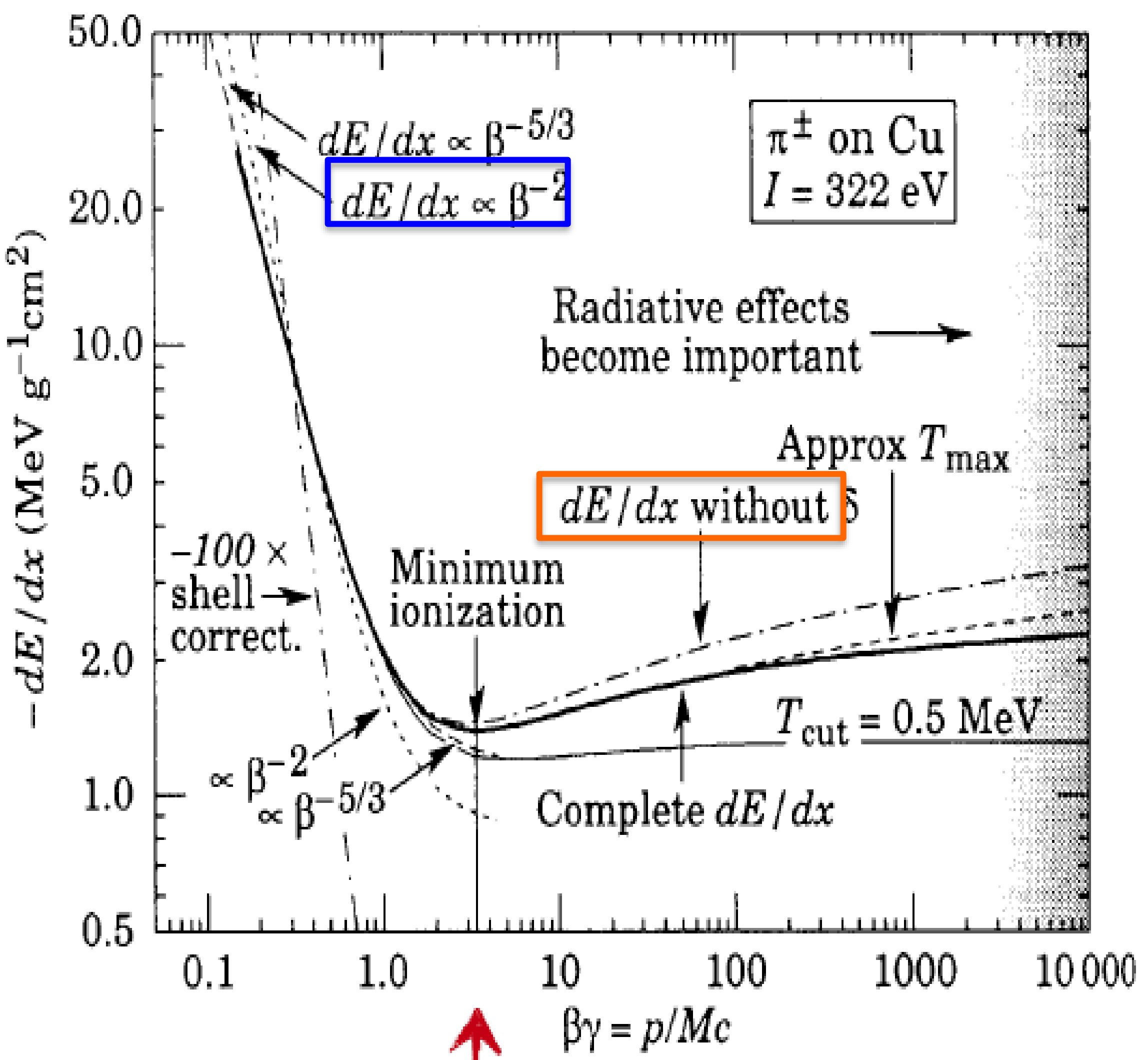
Incident particle

- z = charge of incident particle
- β = v/c of incident particle
- $\gamma = (1-\beta^2)^{-1/2}$
- W_{max} = max. energy transfer in one collision

Note: the classical dE/dx formula contains many features of the QM version: $(z/\beta)^2$, & ln[]

$$-\frac{dE}{dx} = \frac{4\pi N_e z^2 r_e^2 m_e c^2}{\beta^2} \ln \frac{b_{max}}{b_{min}}$$

(Heavy) Charge Particle Energy Loss Due to Ionization



Bethe-Bloch formula

Minimum ionizing particles (MIP): $\beta\gamma$ = 3-4

dE/dx falls ~ β^{-2}; kinematic factor
[precise dependence: ~ $\beta^{-5/3}$]

dE/dx rises ~ $\ln(\beta\gamma)^2$; relativistic rise
[rel. extension of transversal E-field]

Saturation at large ($\beta\gamma$) due to density effect (correction δ)
[polarization of medium]

Units: MeV g^{-1} cm^2

MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm^3]

$\beta\gamma = 3\text{-}4$

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2}\ln\left(a\beta^2\gamma^2\right)$$

Energy Loss dE/dx: Electrons (Positrons)

Electrons (and positrons) are different as they are light

→ Bethe-Bloch formula needs modification

→Incident and target electron have same mass

→ Scattering of identical, undistinguishable particles

Energy loss for electrons/positrons involve mainly two different physics mechanisms:

- **Excitation/ionization**

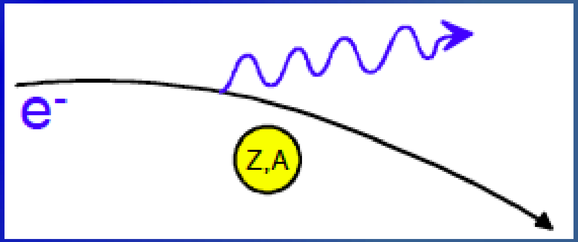
$$-\left\langle \frac{dE}{dx} \right\rangle_{Ionization} \mu \ln(E)$$

But collision between identical particles + electron is now deflected

- **Bremsstrahlung : emission** of photon by scattering with the nucleus electrical field

At high energies radiative processes dominate

$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} \mu \frac{E}{m^2}$$

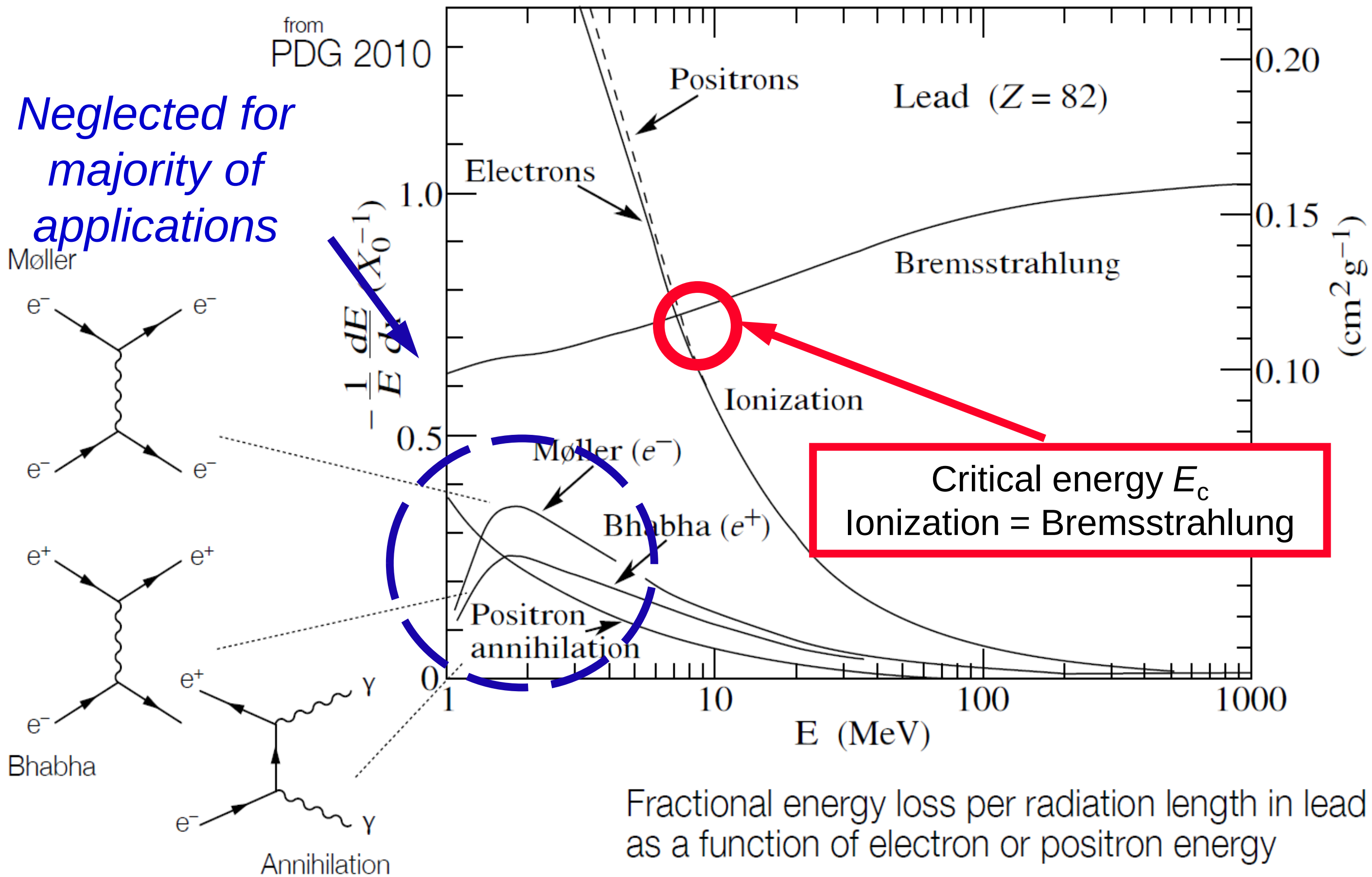


energy loss proportional to 1/m² → main relevance for electrons (or ultra-relativistic muons)

Total Energy Loss for Electrons

Define Radiation Length X_o → as the Radiative Mean Path :

i.e. the distance over which the energy of electron/positron is reduced by a factor e by Bremsstrahlung. Measured in units of [g/cm2]



Fractional energy loss per radiation length in lead as a function of electron or positron energy

$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} = \frac{E}{X_0}$$

X_0 = radiation length in [g/cm²]

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

After passage of one X_0 electron has lost all but $(1/e)^{th}$ of its energy (63%)

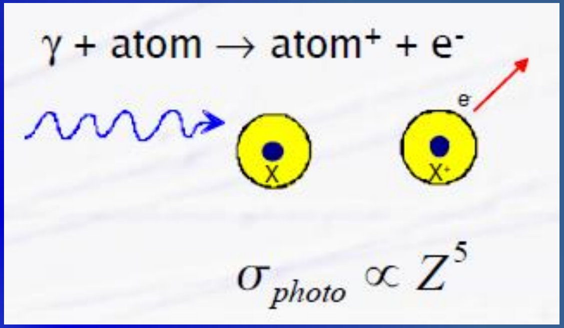
E_c = critical energy

$$\left.\frac{dE}{dx}(E_c)\right|_{Brems} = \left.\frac{dE}{dx}(E_c)\right|_{Ion}$$

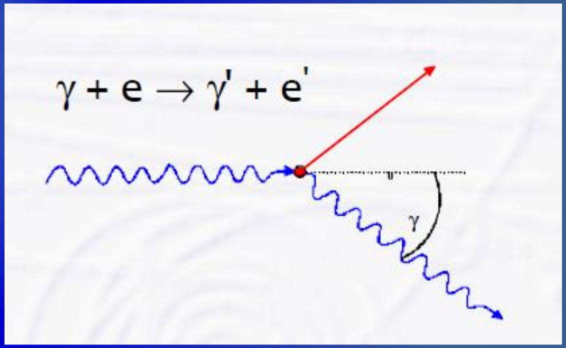
Fractional energy loss per X_o in lead as a function of electron/positron energy

Particle Interactions: Photons

- ***Photo effect***
  - used at various photo detectors to create electrons on photo cathodes in vacuum and gas or at semi conductors (surface)
    - Photo Multiplier Tubes (PMT)
    - Photo diodes

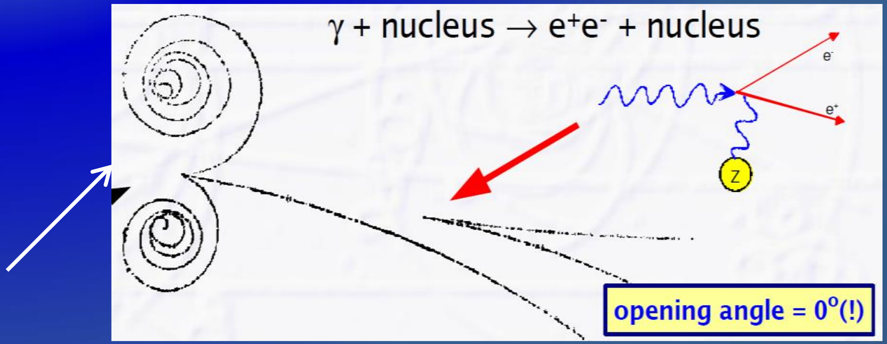


- ***Compton scattering ($e^-\gamma$ scattering)***
  - not used for particle detection
    - was/is used for polarization measurement of beams at e^+e^- machines and could be used to create high energy photons in a gg - collider



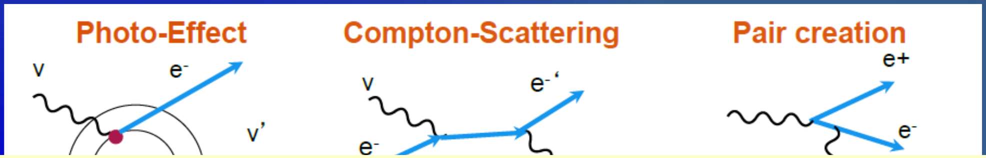
- ***Pair production ($\gamma \rightarrow e^+e^-$)***
  - initiates electromagnetic shower in calorimeters, unwanted in tracking detectors

$\gamma + e^- \rightarrow e^+e^- + e^- + \gamma$



Energy Loss for Photons

Energy loss for photons →
three major physics mechanisms :



For photons, it is not the energy, which is attenuated, but the intensity : photons are absorbed or deviated

- ***Photo electric effect : absorption of a photon by an atom ejecting an electron***

$$\sigma = Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma}\right)^n \quad n = 7/2 \text{ for } E \ll m_e c^2 \text{ and } \rightarrow 1 \text{ for } E \gg m_e c^2$$

Strong dependence with Z, dominant at low photon energy

- ***Compton scattering***

$$\sigma_C^e \propto \frac{\ln E_\gamma}{E_\gamma} \text{ and atomic compton} = Z\,\sigma_C^e$$

- ***Pair creation (similar to bremsstrahlung) :*** dominant for $E \gg m_e c^2$

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}}\right) = \frac{A}{N_A} \frac{7}{9} \frac{1}{X_0}$$

Independent of energy !

Probability of pair creation in 1 X_0 is $e^{-7/9}$, mean free path of a photon before creating a e^+e^- pair is $\Lambda_{pair} = 9/7\ X_0$

Radiation Length (X_0)

- ***Main energy loss of high energy photons/electrons in matter***
  - pair production (γ) and bremsstrahlung ($e^{\pm}$)
- ***Can characterize any material by its radiation length X_0***
  - 2 definitions (for electrons and for photons)
    - X_0 = length after an electron looses all but 1/e of its energy by Bremsstrahlung
    - X_0 = 7/9 of mean free path length for pair prodution by the photon
- ***Very convienient quantity***
  - Rather than using thickness, density, material type etc. detector
    - often expressed as % of X_0
  - ***tracking detectors should have X_0 as low as possible (<< 1 X_0)***
    - ATLAS and CMS trackers: 30% - 130% X_0
    - not really "transparent", high probability to initiate electromagnetic showers in tracker far before electrons/photons reach calorimeters
      - "pre-shower" detectors in front of calorimeter should detect and correct measured ECAL energy for such early showers
  - ***electromagnetic calorimeters should have X_0 as much as possible (typically 20...30 X_0)***

Electromagnetic Cascades (I)

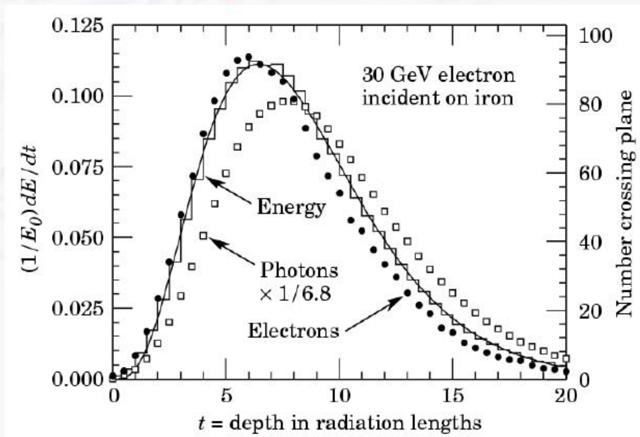
Starting from the first electron/photon electromagnetic shower (cascade) develops in thick materials:

Electron shower in lead.
7500 gauss in cloud chamber.

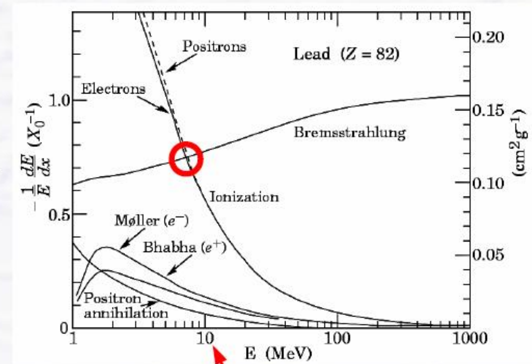
→ **shower maximum (peak of energy deposition) slightly energy dependent**

$$t_{max}[X_0] = \ln\frac{E_0}{E_c}\frac{1}{\ln 2}$$

E_c = critical energy where energy loss (Ionization) = energy loss (Bremsstrahlung)



O (5 - 10 X_0)

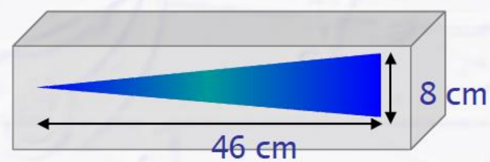


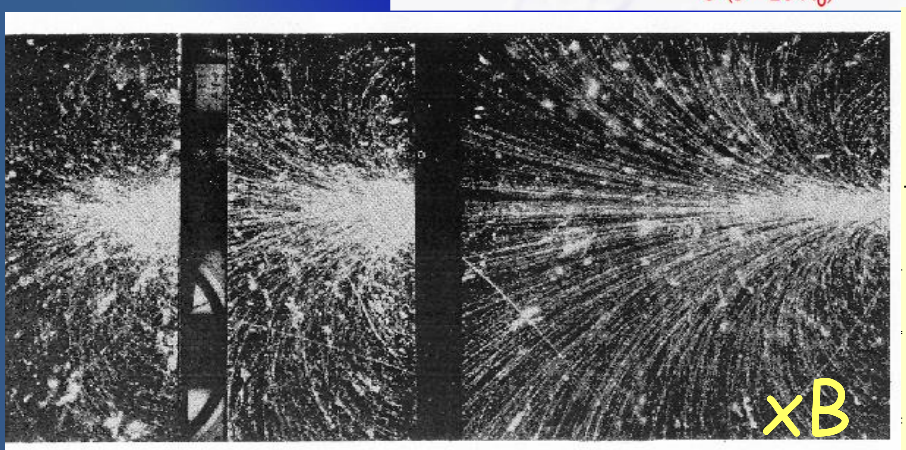
O (10 MeV)

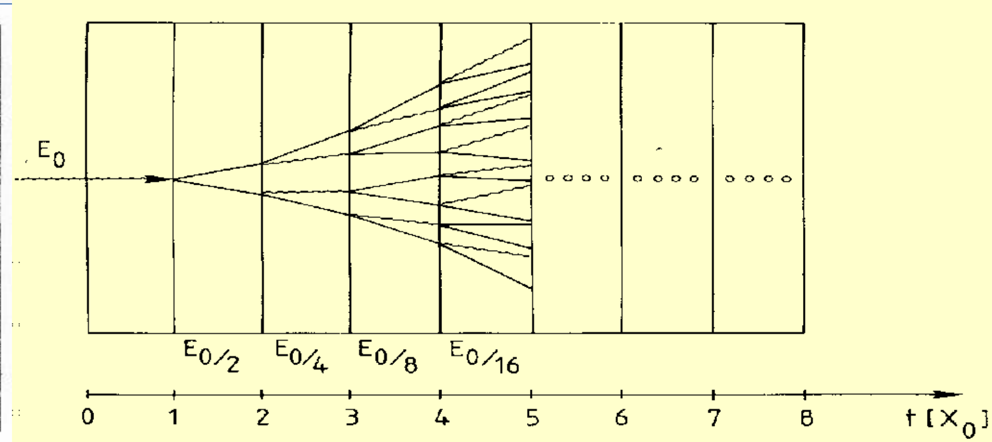
transversal shower width given by Moliere radius

$$R_M = \frac{21\,MeV}{E_c} X_0$$

typically ~ 2 X_0

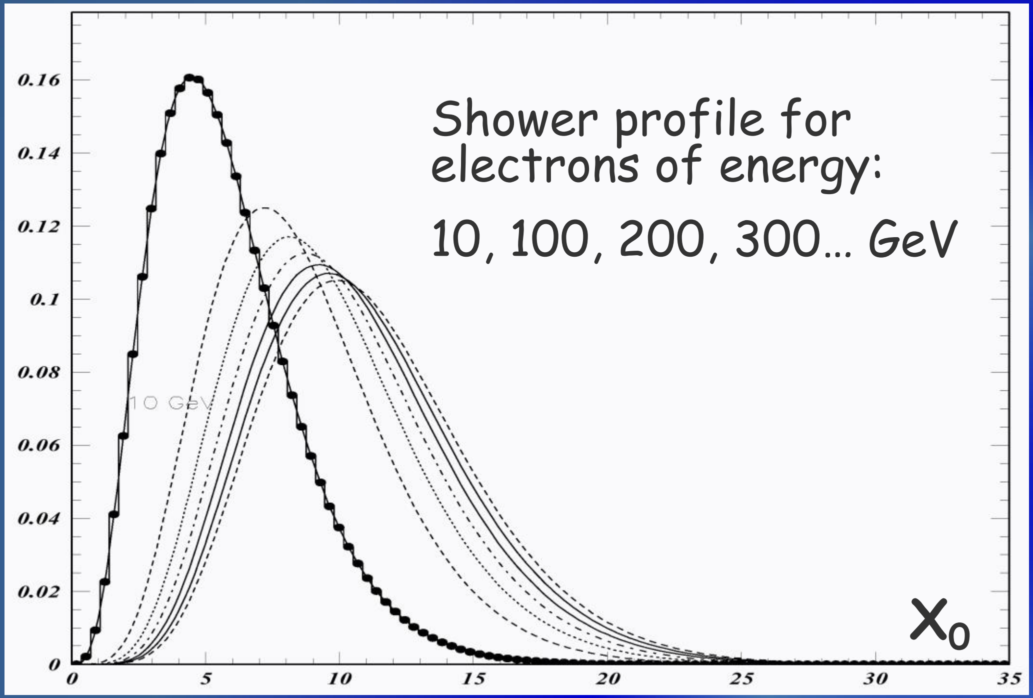






Electromagnetic Cascades (II)

Longitudinal profile



Transverse profile

- ✓ Multiple scattering for electrons
- ✓ Photons with energies in the region of minimal absorption travel away from shower axis

➔ *Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing $1X_0$*

$$R_M = \frac{21\,\text{MeV}}{E_C} X_0$$

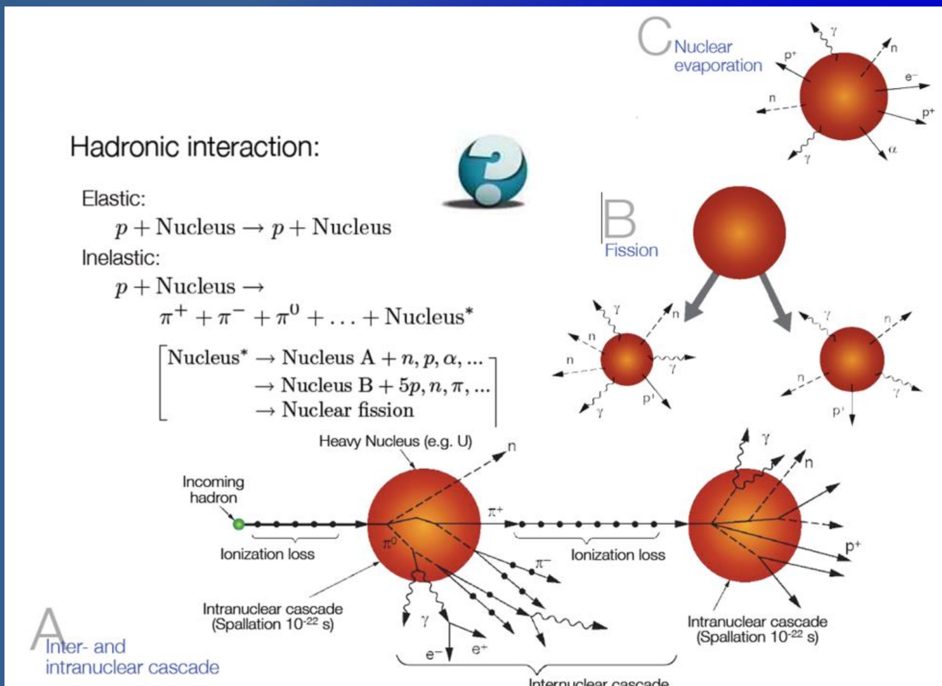
$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} \left(Z >> 1 \right)$$

Transverse shower containment:
75% E_0 within **$1R_M$, 95%** within **$2R_M$, 99%** within **$3.5R_M$**

➔ *Calorimeter granularity !*

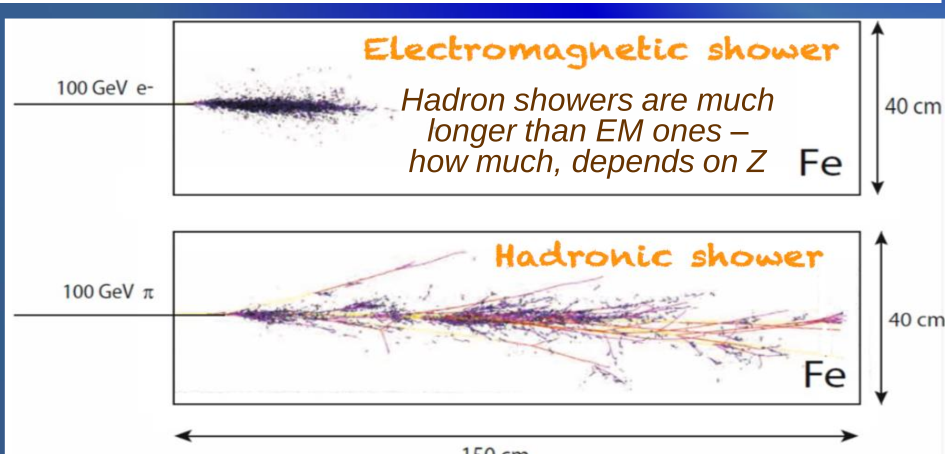
Hadron Showers and Nuclear Interaction Length (λ_I)

Interaction of energetic hadrons (charged/neutral) through matter involves nuclear interaction :
excitation and nucleus break up => production of secondary particles + fragment



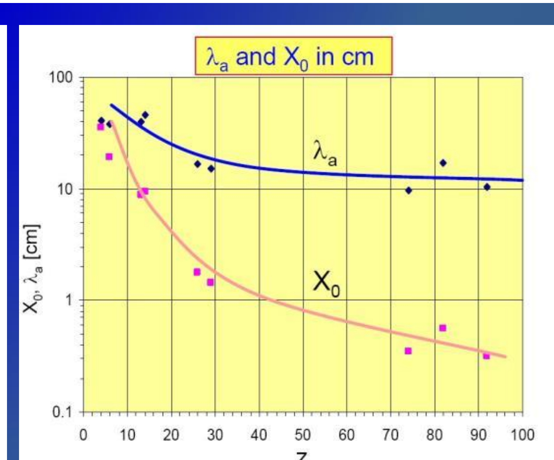
- *Number of particle produced ~ln (E) with average transverse p of 0.35 GeV/c*
- *For E > 1 GeV, $\sigma \sim \sigma_0 A^{0.7}$, with σ_0= 35 mb and independent of particle type π,p,K,…*
- *Convenient to introduce the hadronic nuclear interaction length – mean free path between nuclear collisions*

$$\lambda_{I(a)} = \frac{A}{N_A \sigma_{total(inel)}} \propto A^{1/3}, N = N_0 e^{-\frac{x}{\lambda_a}}$$



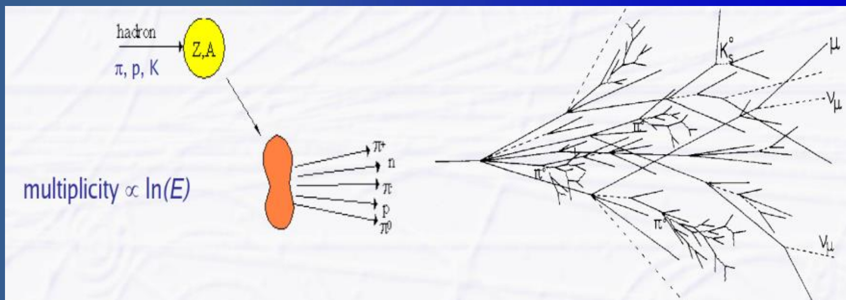
Some numerical values for materials typical used in hadron calorimeters

	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8



Electromagnetic vs. Hadronic Showers

- **Development of hadronic cascade (shower) by strong interaction of hadron with nucleus**



Electromagnetic shower

Size related to X_0 (longitudinal) and ρ_M (transverse)

Longitudinal size: 95% length = ~20-22 X_0

Transverse size: 90% in a cylinder of radius of ρ_M
95% in a cylinder of radius of $2\rho_M$

Hadronic shower

Size related to λ_I (longitudinal and transverse)

Longitudinal size: 95% length = 6-9 λ_i

Transverse size: 95% in a cylinder of radius = λ_I

- **Hadronic showers have two main components**
  - **hadronic**
    - **charged hadrons, breaking up of nuclei (binding energy) nuclear fragments, neutrons**
  - **electromagnetic**
    - **decay of neutral pions: $\pi^0 \rightarrow 2\gamma$ (100% branching ratio)**
- **Hadronic and EM energy component usually have different detector response**
  - **100 GeV hadronic energy is not 100 GeV EM energy response in detector**
  - **In general, hadronic showers are characterized by large fluctuations. complications hadron calorimetry.**

Energy Loss by Photon Emission

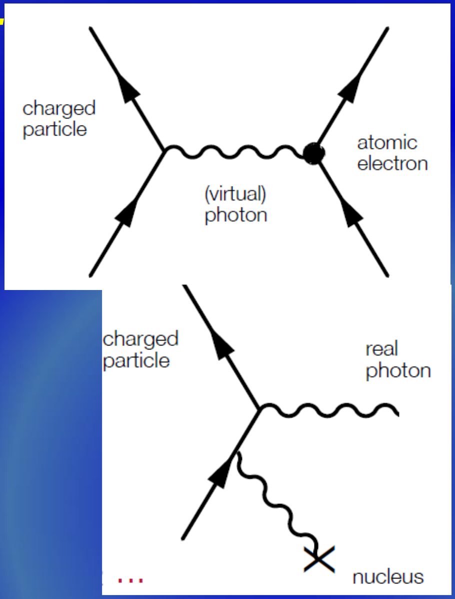
Ionization is one way of energy loss
Emission of photons is another...

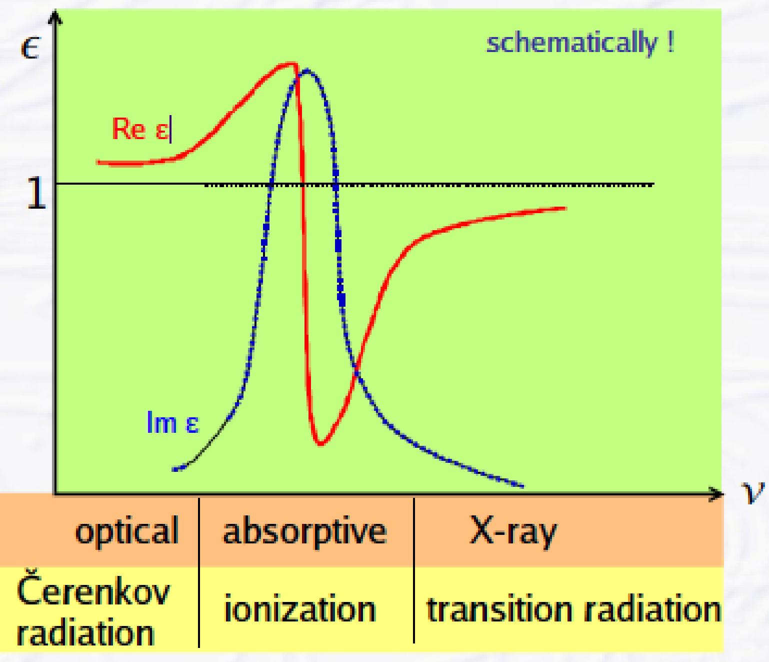
Optical behavior of medium is characterized by the (complex) dielectric constant **ε**

- Re √**ε** = n Refractive index
- Im **ε** = k Absorption parameter

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 \ldots$$

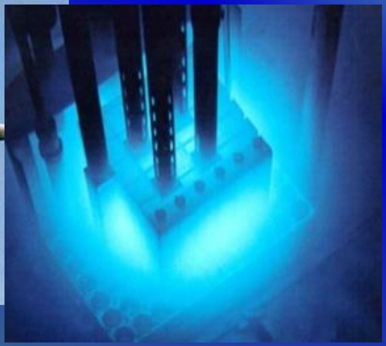
Represents/describes interaction of (virtual) photons with atoms of medium





Cherenkov radiation-

"Sonic boom for charged particles"



Transition Radiation:

- is produced by relativistic charged particles when they cross the interface of two media of different dielectric constants
- significant radiation only at large γ (O ~ 1000) in the keV range.very useful for electron/pion separation

Both effects are not really contributing to the energy loss of the particles!

Cherenkov Radiation Detectors

Unique tool to identify charged particles with a high separation power over a range of momentum from few hundred MeV/c up to several hundred GeV/c

A charged particle with velocity β=v/c greater than local velocity of light in a medium with refractive index n=n(λ) may emit light along a conical wave front.

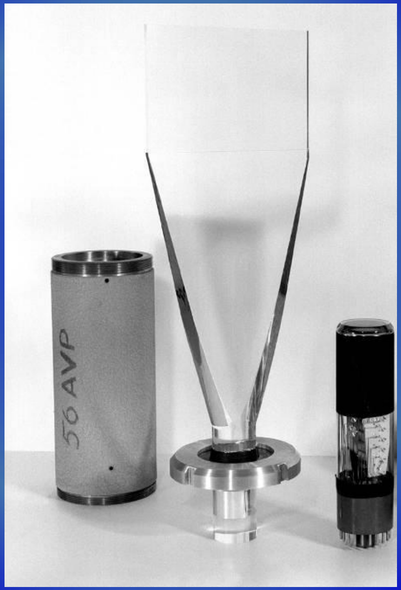
The angle of emission is given:

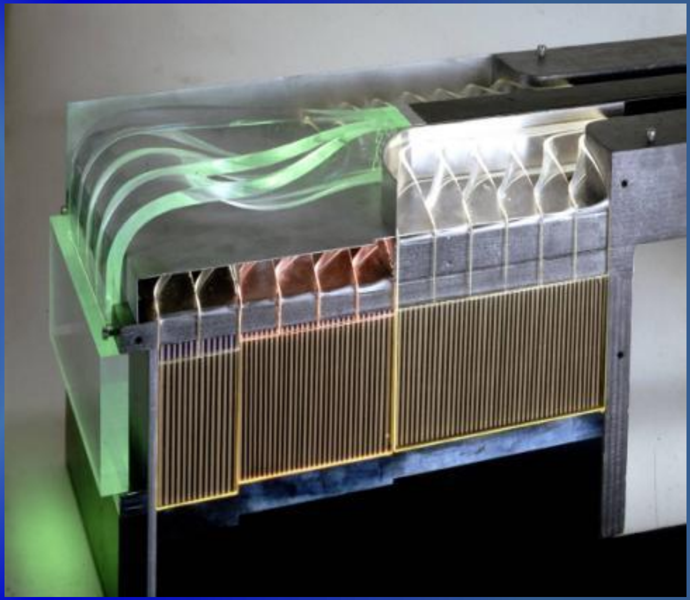
$$-\left\langle \frac{dE}{dx} \right\rangle_{Cherenkov} \mu \; z^2 \sin^2 q_c$$

$$\cos\Theta_C = \frac{1}{\beta \cdot n}$$

$\cos\theta_{max} = 1/n$

$\beta_{min} = 1/n$





Radiator

+

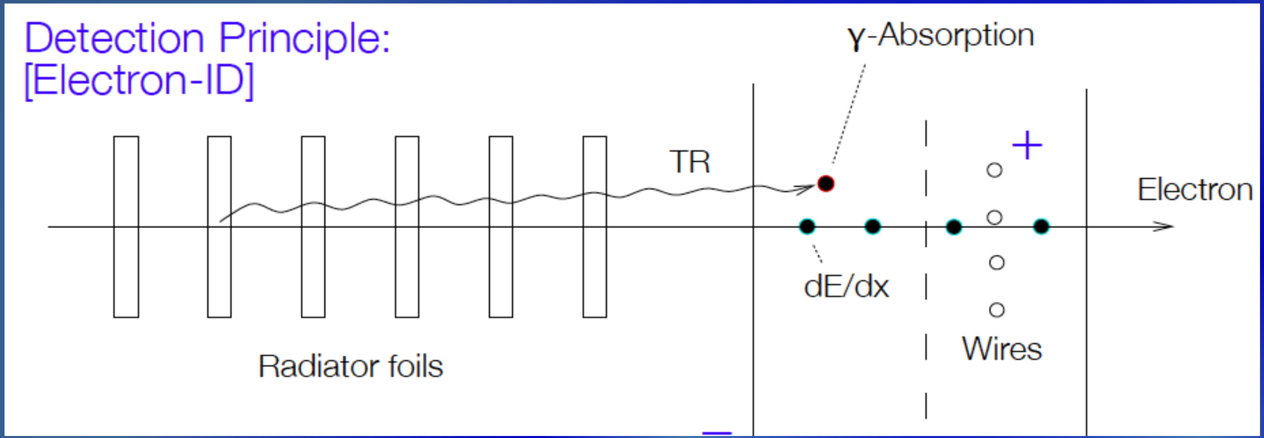
Photon detector

➔ ***Particle ID : Threshold (detect Cherenkov light) and Imaging (measure Cherenkov angle) techniques***

➔ Fast particle counters, tracking detectors, performing complete event reconstruction, ...

Transition Radiation Detectors

- *Use stacked assemblies of low Z material & many transitions + detector with high Z gas*



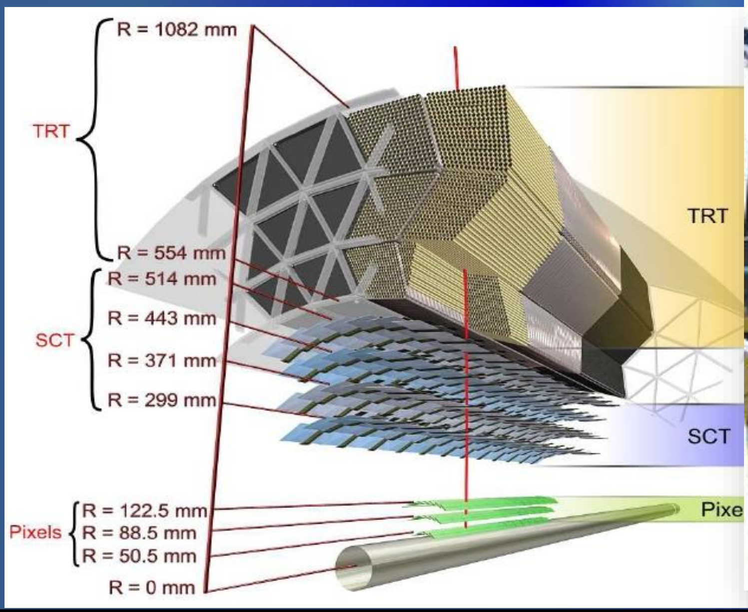
- *Typical emission angle:* $\Theta = 1/\gamma$
- *Energy of radiated photons:* $\sim \gamma$
- *Number of radiated photons:* az^2
- *Effective threshold:* $\gamma > 1000$

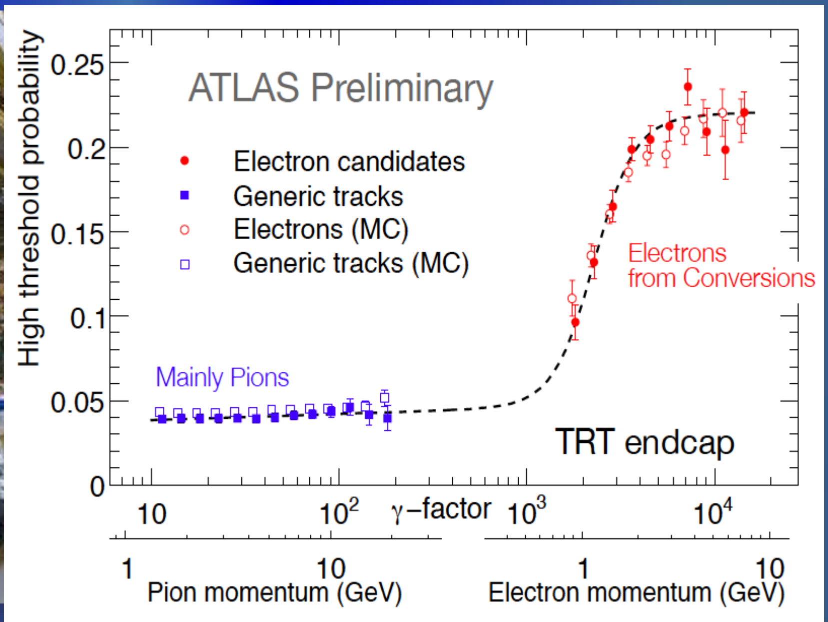
$$S = \frac{1}{3} a z^2 \gamma \hbar \omega_P$$

$$(\hbar \omega_P \approx 20 eV)$$

Example: ATLAS Transition Radiation Tracker (TRT)

- *straw tubes with xenon-based gas mixture*
- *4 mm in diameter, equipped with a 30 μm diameter gold-plated W-Re wire*





Neutron Interactions with Matter

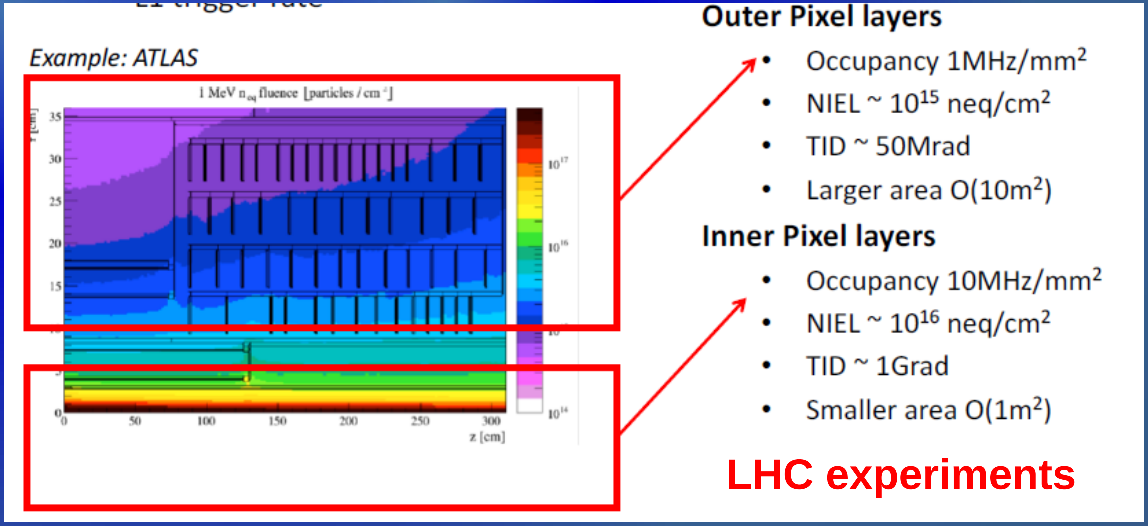
- Neutron has no charge, can be detected only through charged particle produced in (weak or) strong interaction => short range => very penetrating
- Conversion and elastic scattering for E < 1 GeV. For instance

  n + 6Li → α +3H, n+3He → p+3H E < 20 MeV

  n + p → n + p E < 1 GeV
- Hadronic cascade for E > 1 GeV
- Neutrons can travel sometimes for more than 1 μs in detectors

  → outside electronics readout window …

- A lot of low energy neutrons produced in LHC experiments Interactions in the whole cavern (see e.g. ATLAS exp.)
- For the future FCC-pp project, aniticipated neutron fluxes are ~10^{18} n/cm2 eq → non of the existising Si/pixel detector technology are able to tolerate such fluxes



Neutrino Interactions with Matter

- Only weak interaction

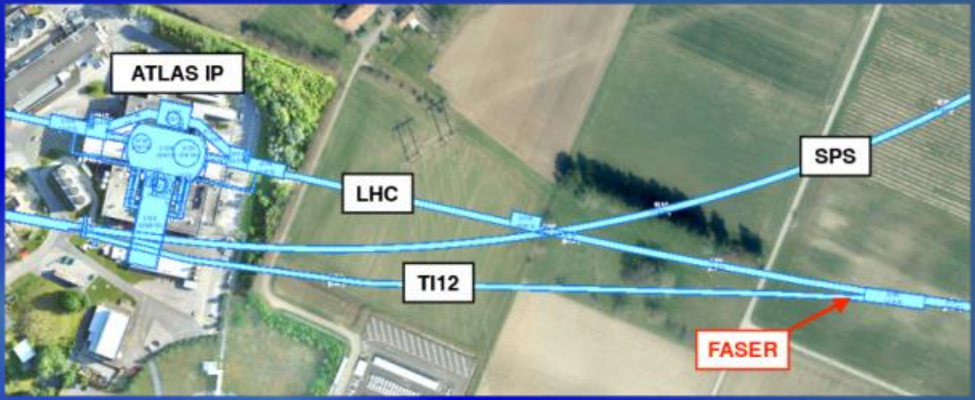
- *$\nu + n$ → l- + p or anti ν + p → l+ + n → detect the charged lepton and the nucleon recoil*

- *Detection efficiency in ~1 m iron about 6.10-17…*
- *Whatever technological improvement, neutrinos detector can only be huge detector*

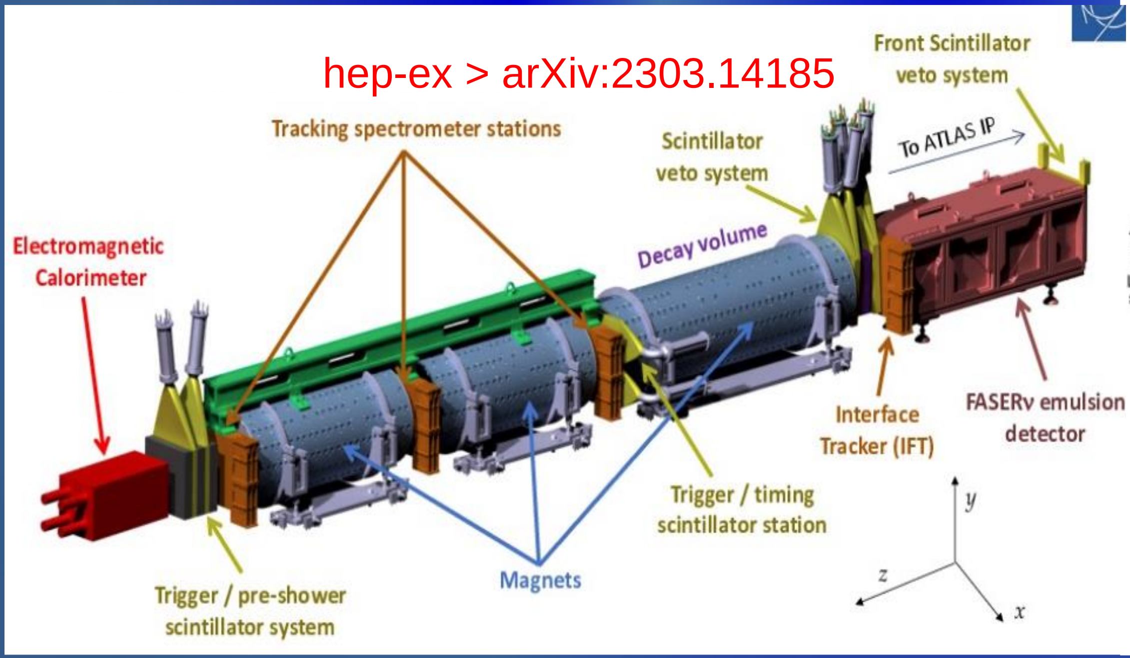
- In collider experiment, indirect detection :
  → Fully" hermetic detector (!)
  → Sum all visible energy/momentum
  → Use beam energy constraint neutrino(s) are taking the missing energy/momentum

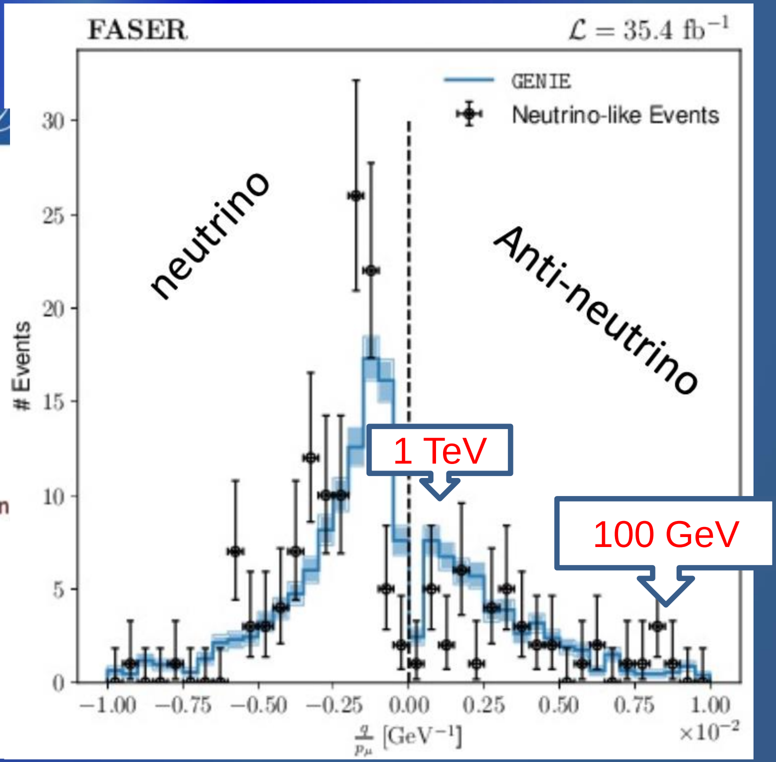
FASER Experiment at CERN

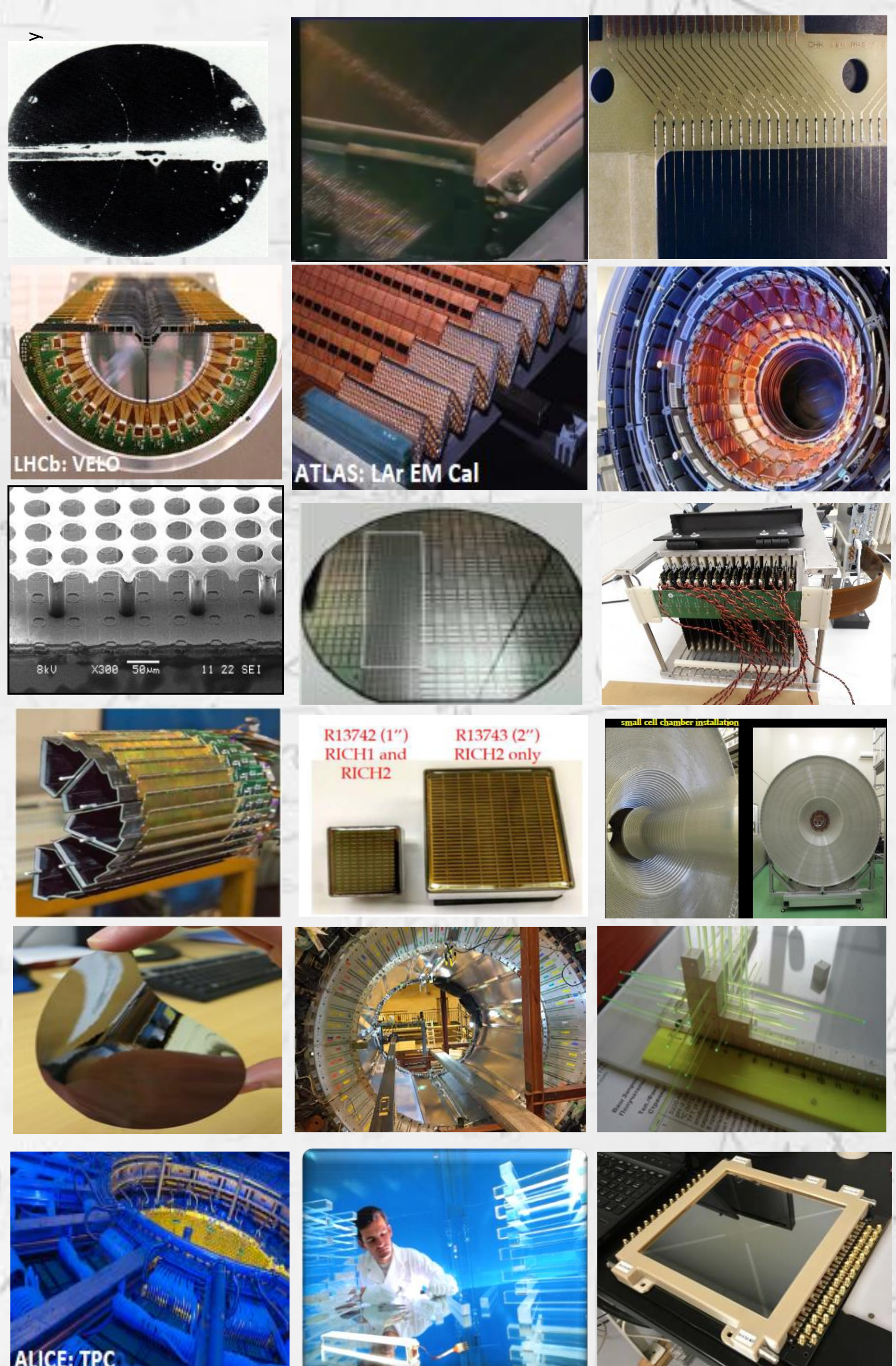
- First Direct Observation of Collider Neutrinos with FASER at the LHC
- ✓ Expect 151 ± 40 events
- ✓ Background estimate: 0.2 events
- ✓ 153 event observed (16 σ)



FASER is ideally positioned to detect the particles into which light and weakly interacting particles will decay. FASER also has a subdetector called FASERv, which is specifically designed to detect neutrinos.



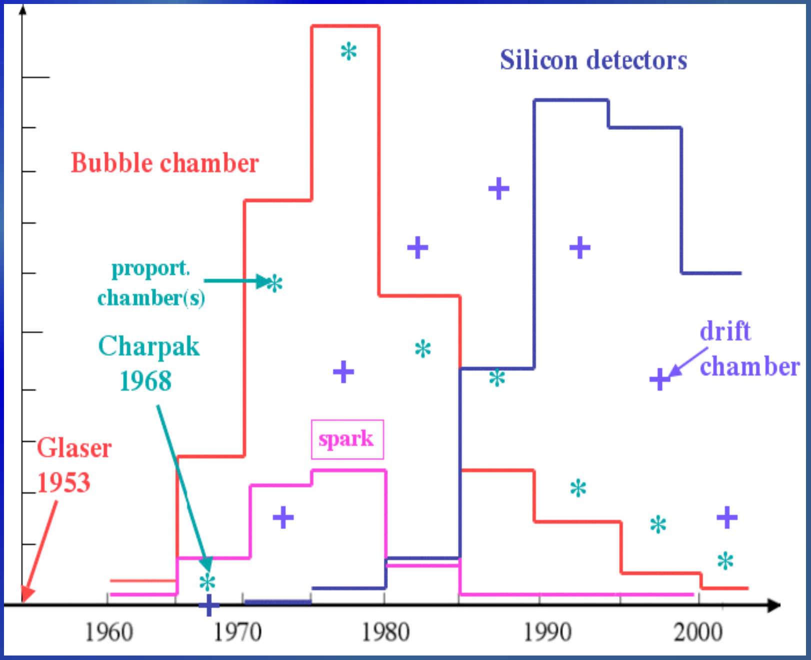




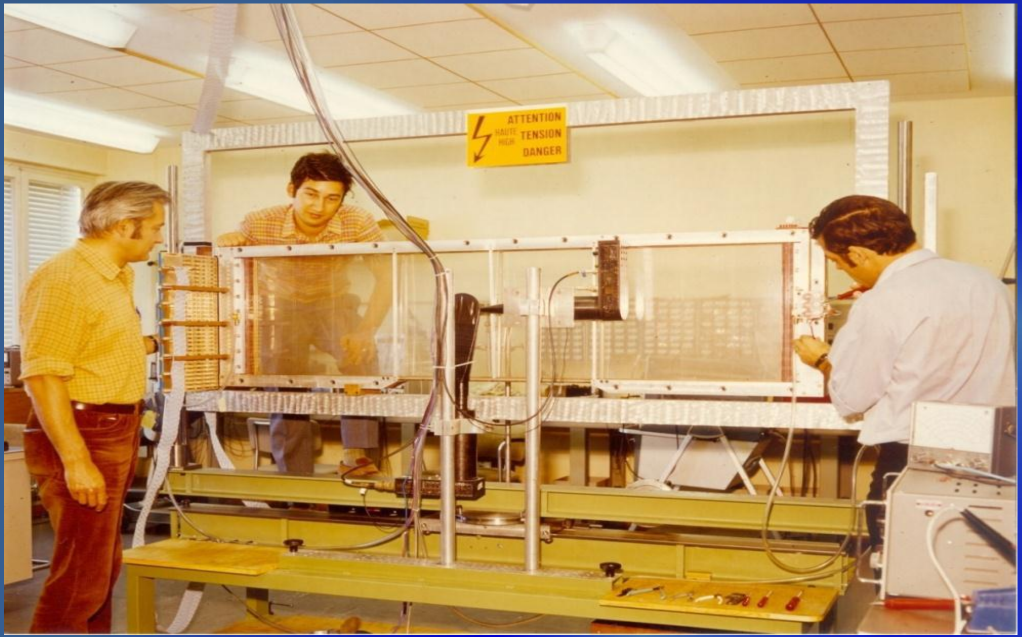
- Particle Interactions with Matter
- "Classic Detectors" (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

"Classic Detectors": Some History and Trends

- **Cloud Chambers, Nuclear Emulsions + Geiger-Müller tubes**
  → dominated until the early 1950s: Cloud Chambers now very popular in public exhibitions related to particle physics
- **Bubble Chambers had their peak time between 1960 and 1985**
  → last big bubble chamber was BEBC at CERN
- **Since 1970s: Wire Chambers (MWPCs and drift chambers) started to dominate; recently being replaced by Micro-Pattern Gas Detectors (MPGD)**
- **Since late 1980s: Solid state detectors are in common use**
  → started as small sized vertex detectors (at LEP and SLC)
  → now ~200 m^2 Si-surface in CMS tracker
- **Most recent trend: silicon strips & hybrid detectors, 3D-sensors, CMOS Monolithic Active Pixel Sensors (MAPS)**

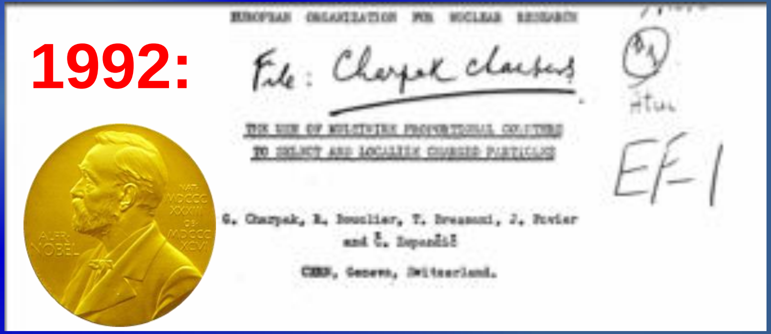


1968: MWPC – Revolutionising the Way Particle Physics is Done



Detecting particles was a mainly a manual, tedious and labour intensive job – unsuited for rare particle decays

1968: George Charpak developed the MultiWire Proportional Chamber, which revolutionized particle detection and High Energy Physics - which passed from the manual to the electronic era.



Electronic particle track detection is now standard in all particle detectors

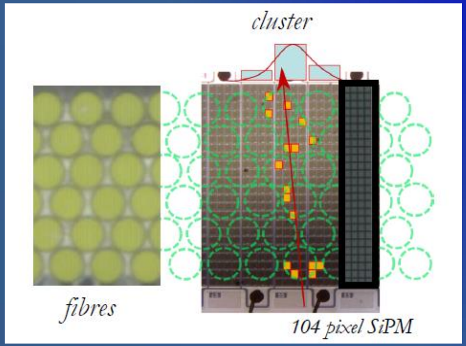
State-of-the-Art in Tracking and Vertex Detectors

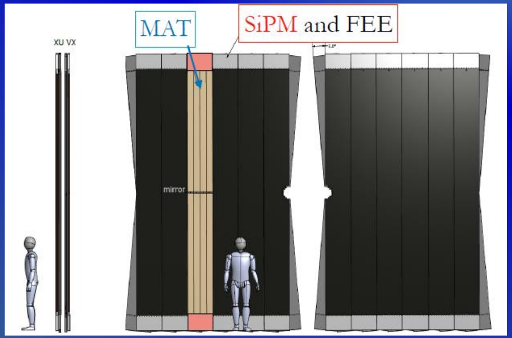
Today's 3 major technologies of Tracking Detectors:

Silicon (strips, pixels, 3D, CMOS, monolithic):
→ electron – hole pairs in solid state material

Gaseous (MWPC, TPC, RPC, MPGDs):
→ ionization in gas

Fiber Trackers: → scintillation light detected with photon detectors (sensitive to single electrons)





LHCb Tracker Upgrade (Sci-fibers with SiPM readout):

Jinst
Published by IOP Publishing for Sissa Medialab
Received: June 12, 2020
Accepted: June 28, 2020
Published: October 22, 2020

International Conference on Instrumentation for Colliding Beam Physics
Novosibirsk, Russia
24–28 February, 2020

M. Titov, JINST15 C10023 (2020)

Next frontiers in particle physics detectors: INSTR2020 summary and a look into the future

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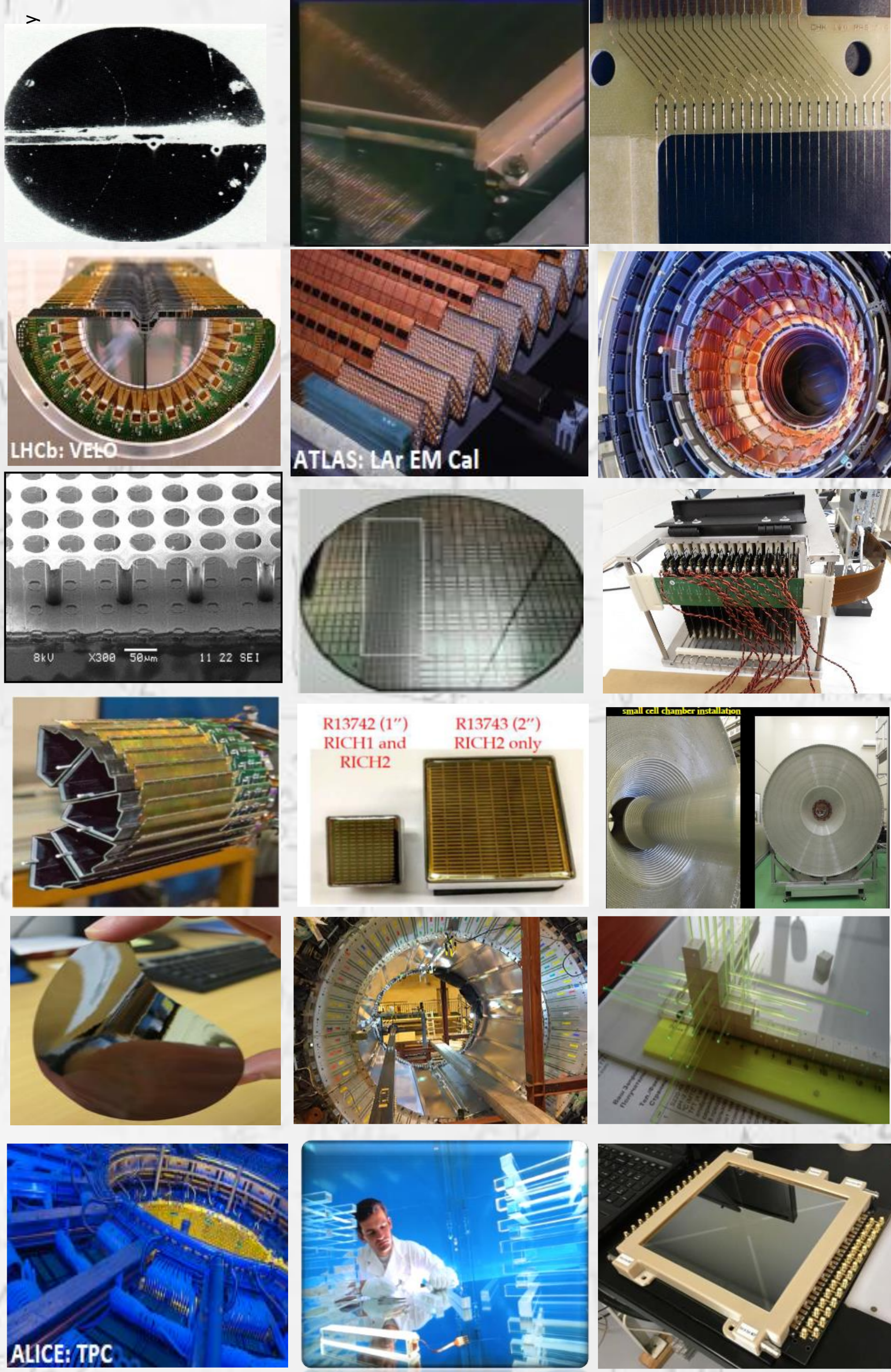
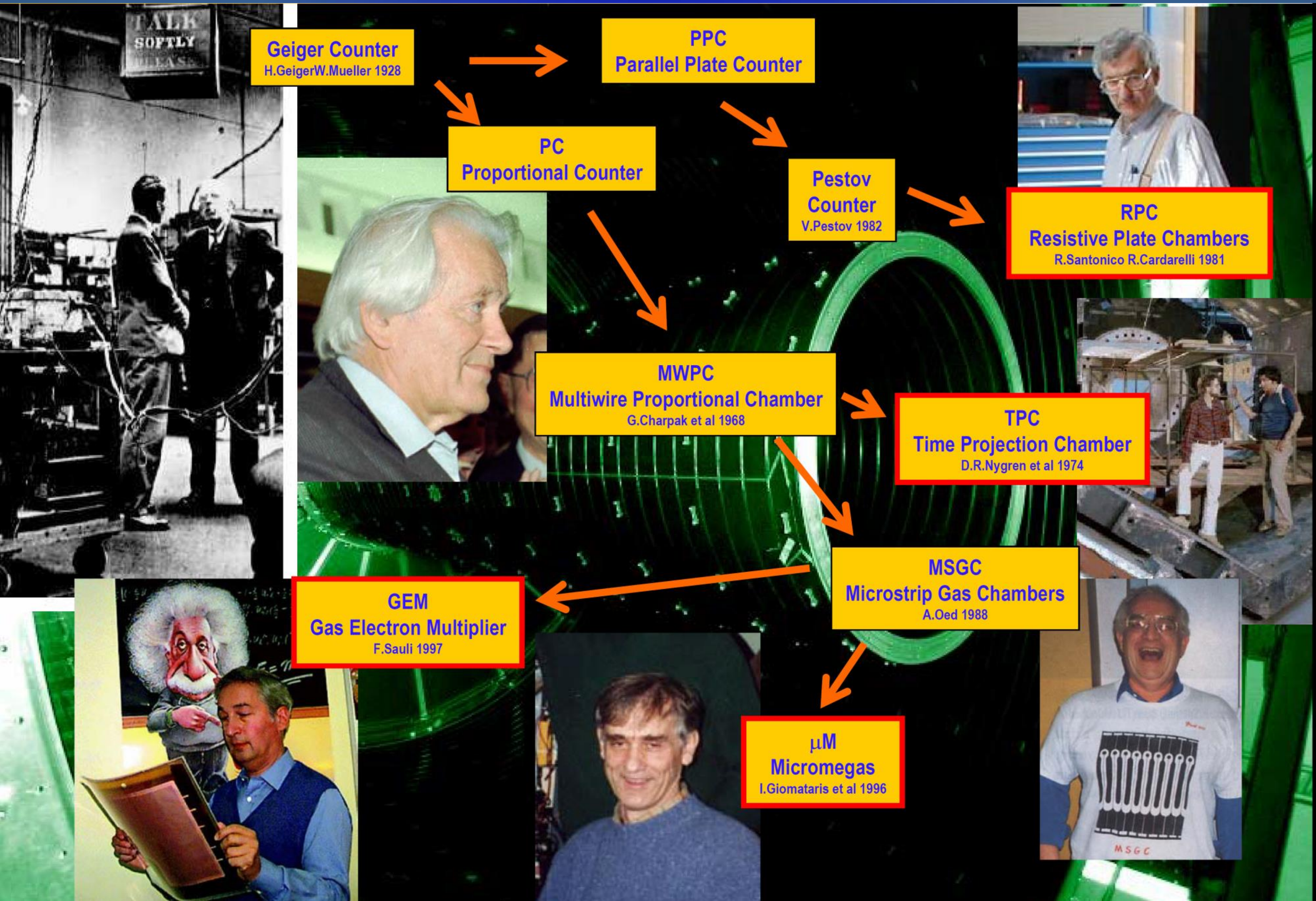
E-mail: maxim.titov@cea.fr



- **Particle Interactions with Matter**
- **"Classic" Detectors (historical touch...)**
- **Advancing Concepts Tracking Detectors: Gaseous Detectors**
- **Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors**
- **Advancing Concepts in Picosecond-Timing Detectors**
- **Advanced Concepts in Particle Identification (PID) & Photon Detectors**
- **Advanced Concepts in Calorimetry**
- **Advanced Concepts in TDAQ, Computing**

Gaseous Detectors: A Brief History



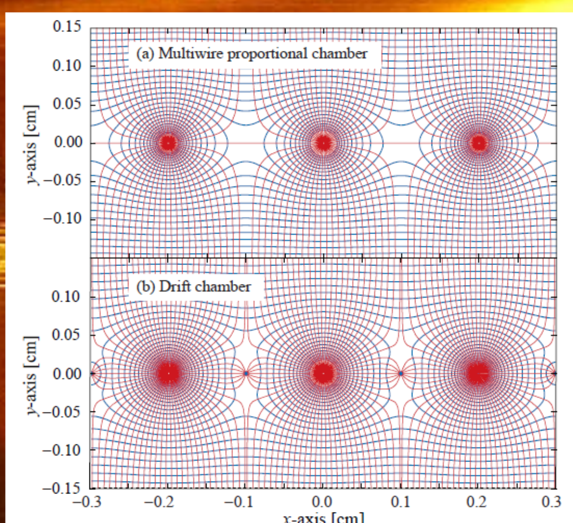
1983/1984: Discovery of W and Z Bosons at UA1/UA2

UA1 used the largest wire / drift chamber of its day (5.8 m long, 2.3 m in diameter)

It can be seen in the CERN Microcosm Exhibition

Discovery of W and Z bosons
C. Rubbia & S. Van der Meer,

1984:



Z → *ee* (white tracks) at UA1/CERN

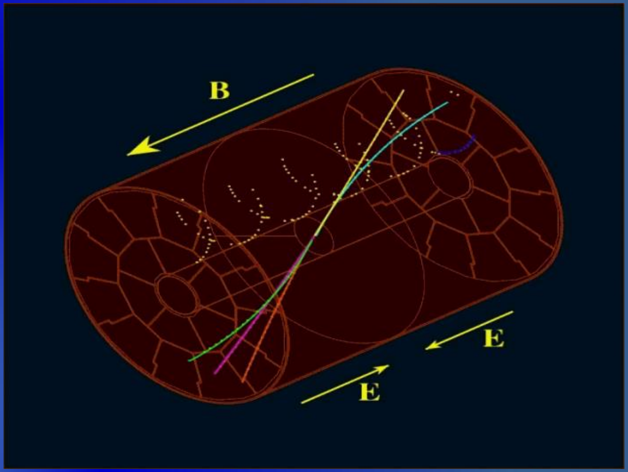
Time Projection Chamber (TPC) in Particle and Ion Physics

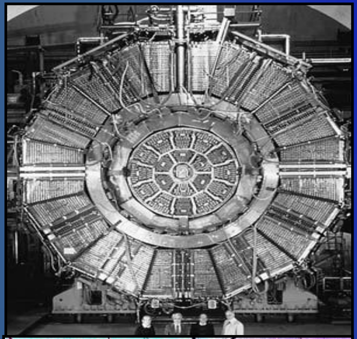
PEP4 (SLAC)

ALEPH (CERN)

- ✓ **Invented by David Nygren (Berkeley) in 1974**
- ✓ **Proposed as a central tracking device for the PEP-4 detector @ SLAC in 1976**
- ✓ **More (and even larger) were built, based on <u>MWPC readout</u>, serving as a powerful tool for:**
  - **- Lepton Colliders (LEP, Higgs Factories)**
  - **- Modern heavy ion collisions (RHIC, EIC)**
  - **- Liquid and high pressure TPCs for neutrino and dark matter searches**

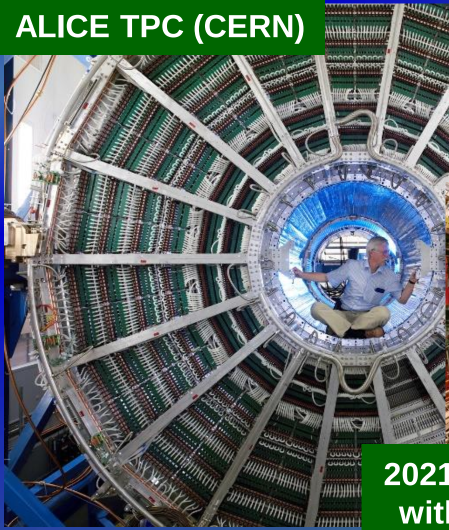
An ultimate drift chamber design is TPC concept - 3D precision tracking with low material budget & PID through differential energy loss dE/dx measurement and/or cluster counting dN_{cl}/dx tech.





	STAR	ALICE	ILC
Inner radius (cm)	50	85	32
Outer radius (cm)	200	250	170
Length (cm)	2 * 210	2 * 250	2 * 250
Charge collection	wire	wire	MPGD
Pad size (mm)	2.8 * 11.5 6.2 * 19.5	4 * 7.5 6*10(15)	2 * 6
Total # pads	140000	560000	1200000
Magnetic field [T]	0.5	0.5	4
Gas Mixture	Ar/CH4 (90:10)	Ne/CO2 (90:10)	Ar/CH4/CO2 (93:5:2)
Drift Field [V/cm]	135	400	230
Total drift time (μs)	38	88	50
Diffusion σ_T ($\mu m/\sqrt{cm}$)	230	220	70
Diffusion σ_L ($\mu m/\sqrt{cm}$)	360	220	300
Resolution in rφ (μm)	500-2000	300-2000	70-150
Resolution in rz (μm)	1000-3000	600-2000	500-800
dE/dx resolution [%]	7	7	< 5
Tracking efficiency[%]	80	95	98

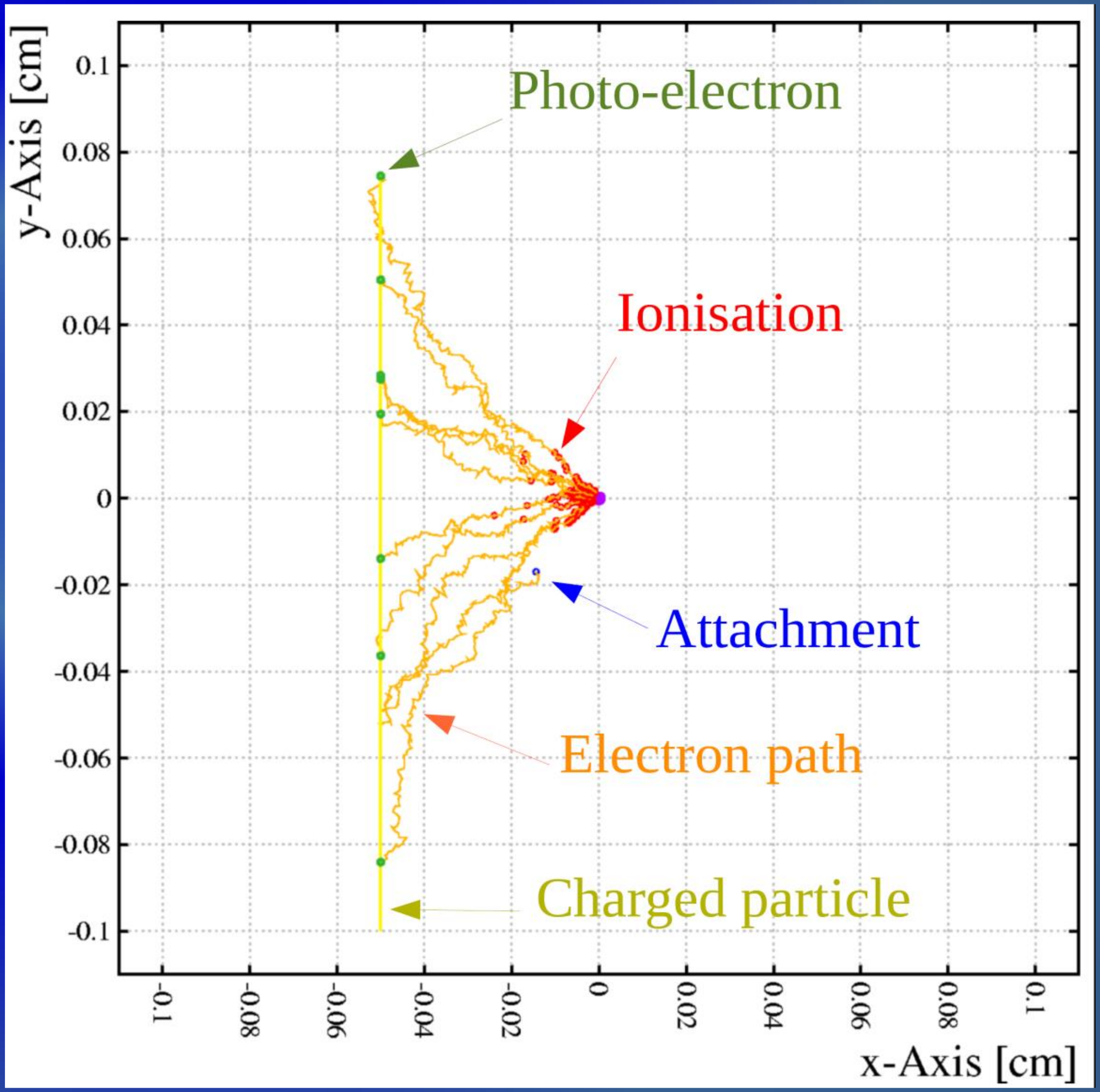
<u>New generation of TPCs use MPGD-based readout:</u> e.g. ALICE Upgrade, T2K, ILC, CepC



Gaseous Detectors: Working Principle

- ✓ a charged particle passing through the gas ionizes a few gas molecules;
- ✓ the electric field in the gas volume transports the ionisation electrons and provokes multiplication;
- ✓ the movement of electrons and ions leads to induced currents in electrodes;
- ✓ the signals are processed and recorded.

At the 100 µm – 1 mm scale:



Example:

- 10 GeV muon crossing
- Gas mixture: Ar/CO2 (80:20) %
- Electron are shown every 100 collisions, but have been tracked rigorously.
- Ions are not shown.

Ionization Statistics: Table for Most Common Gases

Table 35.1: Properties of noble and molecular gases at normal temperature and pressure (NTP: 20° C, one atm). E_X, E_I: first excitation, ionization energy; W_I: average energy for creation of ion pair; $dE/dx|_{\min}$, N_P, N_T: differential energy loss, primary and total number of electron-ion pairs per cm, for unit charge minimum ionizing particles. Values often differ, depending on the source, and those in the table should be taken only as approximate.

Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{\min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
H_2	0.084	10.8	13.6	37	0.34	5.2	9.2
He	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	0.839	16.7	21.6	37	1.45	13	40
Ar	1.66	11.6	15.7	26	2.53	25	97
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	28	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	35-52	6.38	52-63	120

F. Sauli, M. Titov, Review of Particle Physics, Particle Data Group (2024)

Ar/CO_2 (70/30):

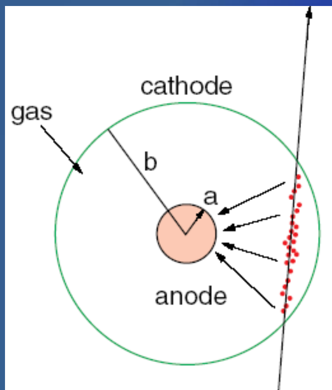
$$N_P = 25 \cdot 0.7 + 35 \cdot 0.3 = 28 \frac{\text{pairs}}{\text{cm}}; \quad N_T = \frac{2530}{26} \cdot 0.7 + \frac{3350}{35} \cdot 0.3 \approx 97 \frac{\text{pairs}}{\text{cm}}.$$

N_T ~ 100 e-ion pairs during ionization process (typical number for 1 cm of gas) is not easy to detect → typical noise of modern pixel ASICs is ~ 100e- (ENC)

Need to increase number of e-ion pairs → … ☹ … how ??? → GAS AMPLIFICATION

Single Wire Proportional Counter: Avalanche Development

Thin anode wire (20 – 50 um) coaxial with cathode

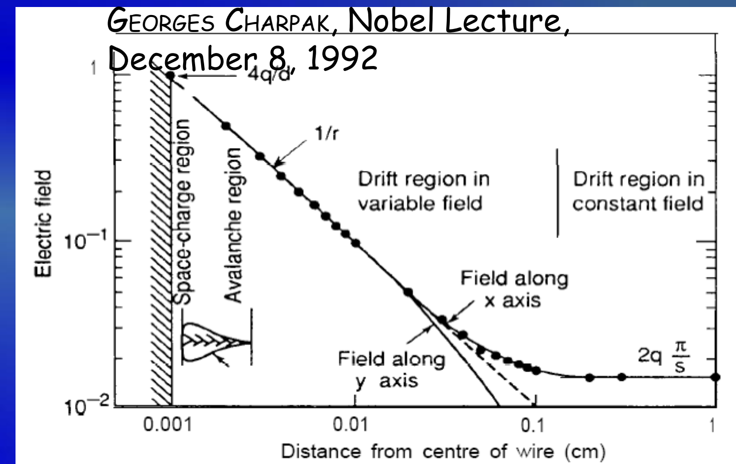


Electric field:

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

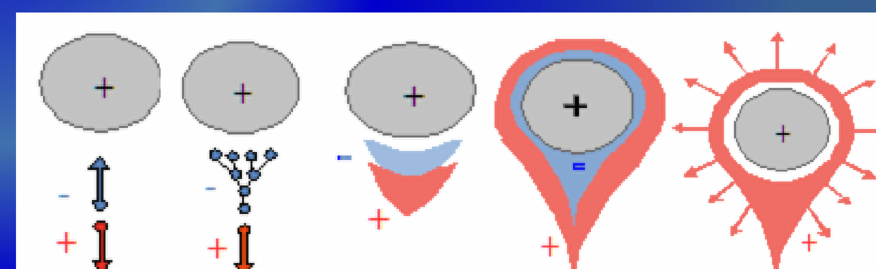
$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$

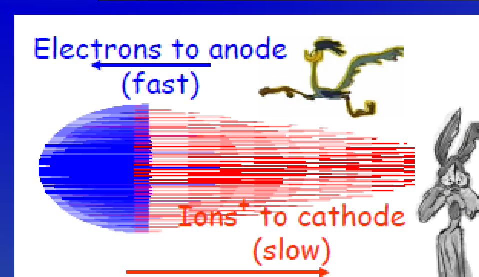
Avalanche development in the high electric field around a thin wire (multiplication region ~< 50 um):

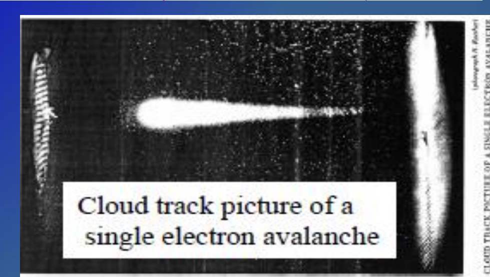


- *Strong increase of E-field close to the wire*
  - → ***electron gains more and more energy***
- *Above some threshold (>10 kV/cm)*
  - → *electron energy high enough to ionize other gas molecules*
  - → *newly created electrons also start ionizing*
- *Avalanche effect: exponential increase of electrons (and ions)*
- *Measurable signal on wire*
  - → *organic substances responsible for "quenching" (stopping) the discharge*

Different stages in the gas amplification process next to the anode wire.



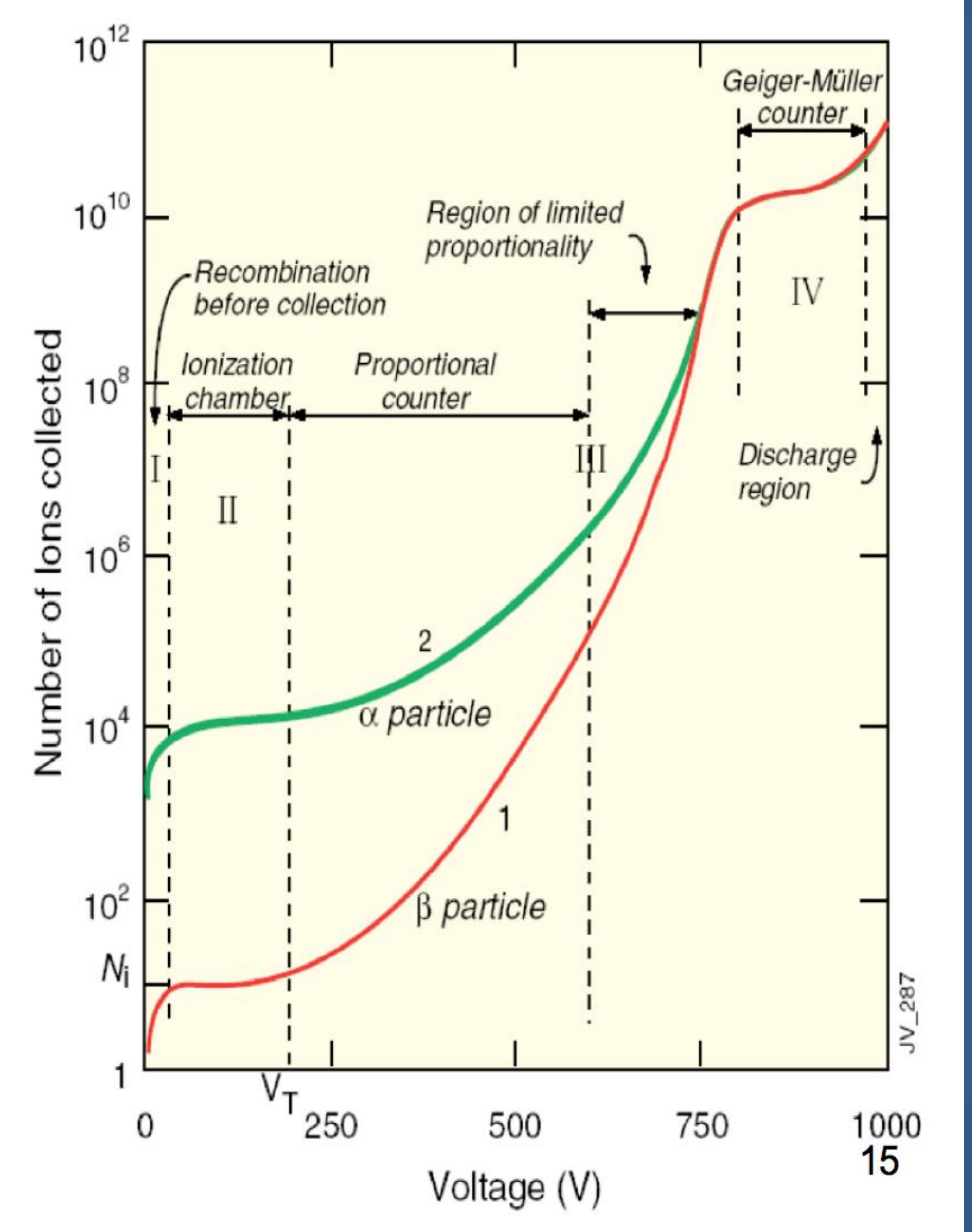




Cloud track picture of a single electron avalanche

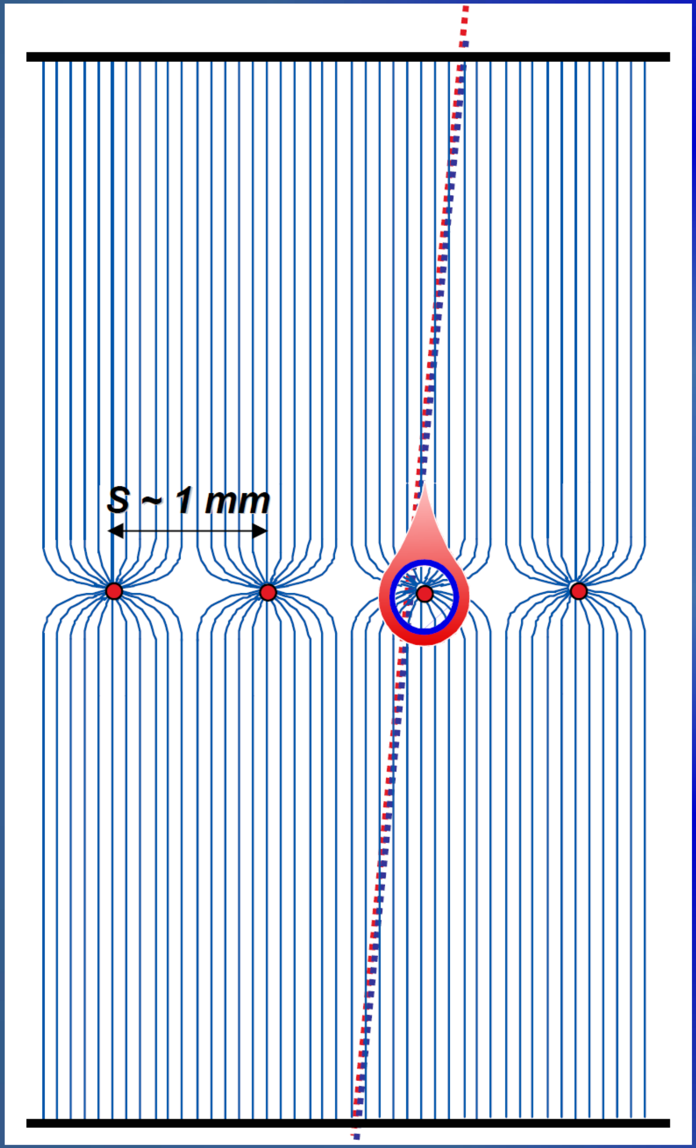
Operation Modes of Gas Detector: Gain-Voltage Characteristics

- ✓ ***Ionization mode (II):***
  - *→ full charge collection, but no multiplication – gain = 1*
- ✓ ***Proportional mode (IIIA):***
  - *→ Multiplication of ionization starts; detected signal proportional to original ionization → possible energy measurement (dE/dx)*
  - *→ proportional region (gain ~ 10^3 – 10^4)*
  - *→ semi-proportional region (gain ~ 10^4 – 10^5), space charge effects*
  - *→ secondary avalanches need quenching*
- ✓ ***Limited proportional mode (saturated, streamer) (IIIB):***
  - *→ saturation (gain > 10^6), independent of number of primary electrons*
  - *→ streamer (gain > 10^7), avalanche along the particle track*
- ✓ ***Geiger mode (IV):***
  - *→ Limited Geiger region: avalanche propogated by UV photons;*
  - *→ Geiger region (gain > 10^9), avalanche along the entire wire*



Multi-Wire Proportional Chamber (MWPC)

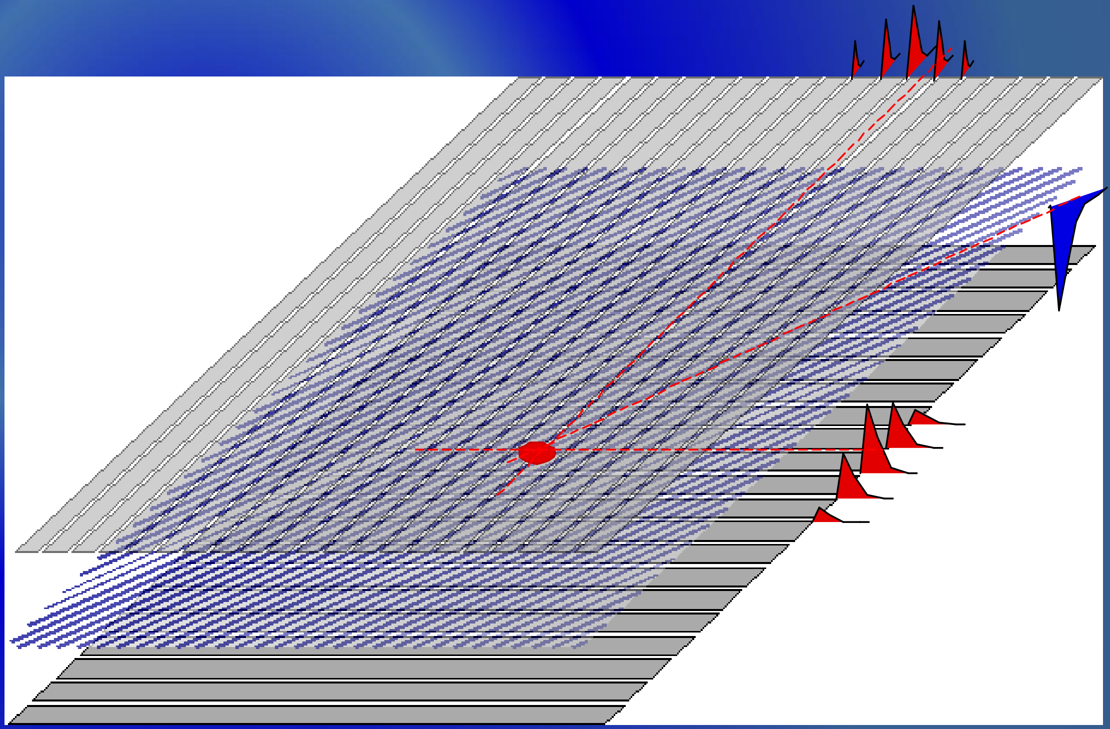
Simple idea to multiply SWPC cell → First electronic device allowing high statistics experiments !!



High-rate MWPC with digital readout:

Spatial resolution is limited to $s_x \sim s/\text{sqrt}(12) \sim 300\ \mu m$

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)



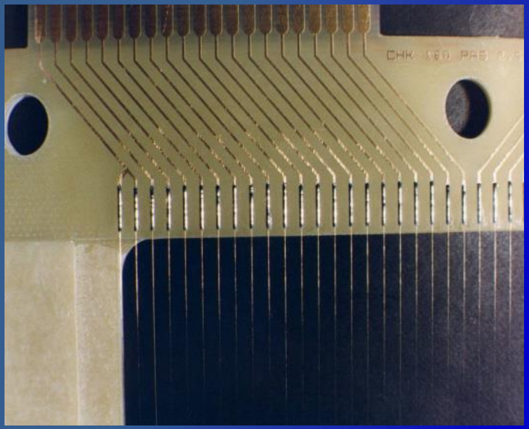
Spatial resolution determined by: Signal / Noise Ratio

Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e

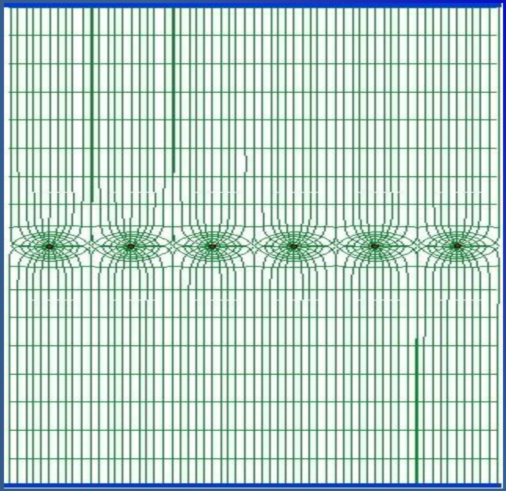
Space resolution < 100 μm

Micro-Strip Gas Chamber (MSGC): An Early MPGD

Multi-Wire Proportional Chamber (MWPC)

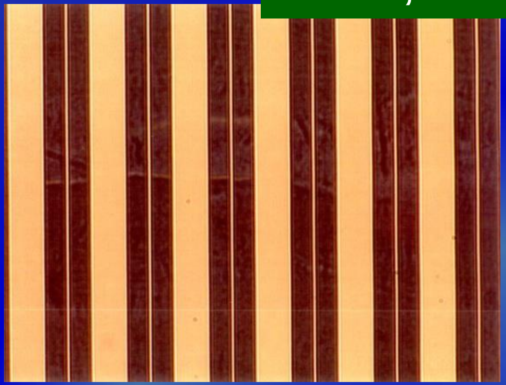


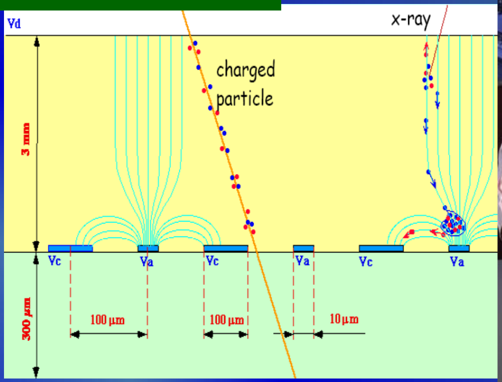
Typical distance between wires limited to ~1 mm due to mechanical and electrostatic forces

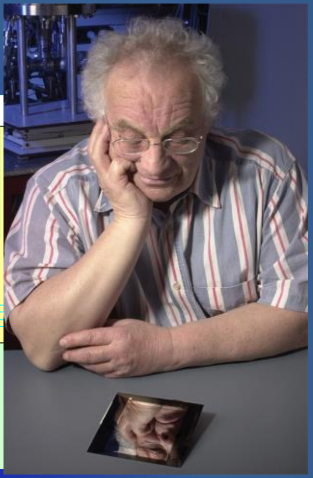


Micro-Strip Gas Chamber (MSGC)

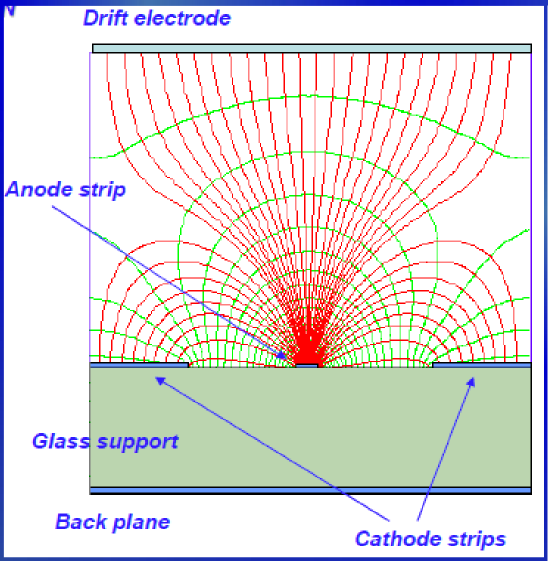
A. Oed, NIMA263 (1988) 351





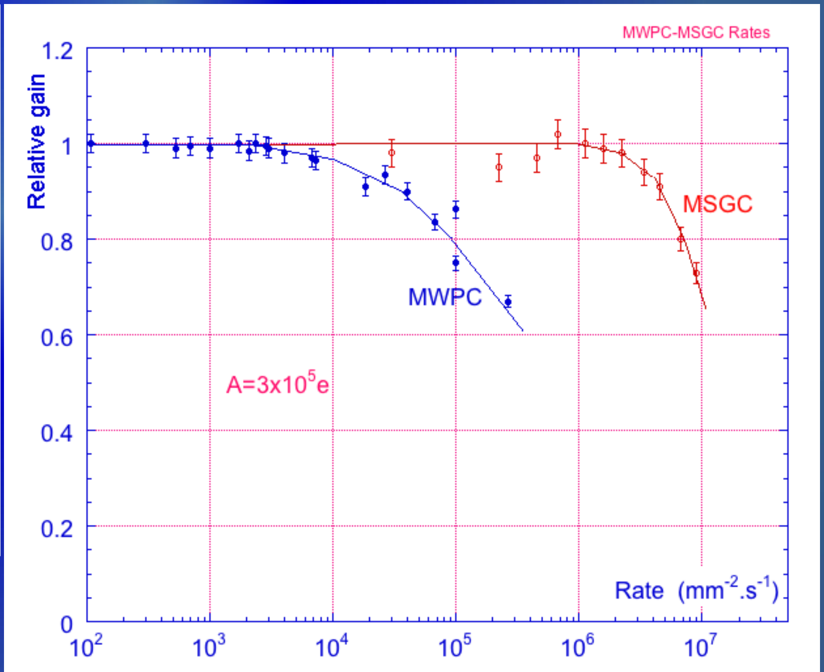


Excellent spatial resolution



Typical distance between electrodes ~100 μm

MSGC significantly improves rate capability due to fast removal of positive ions

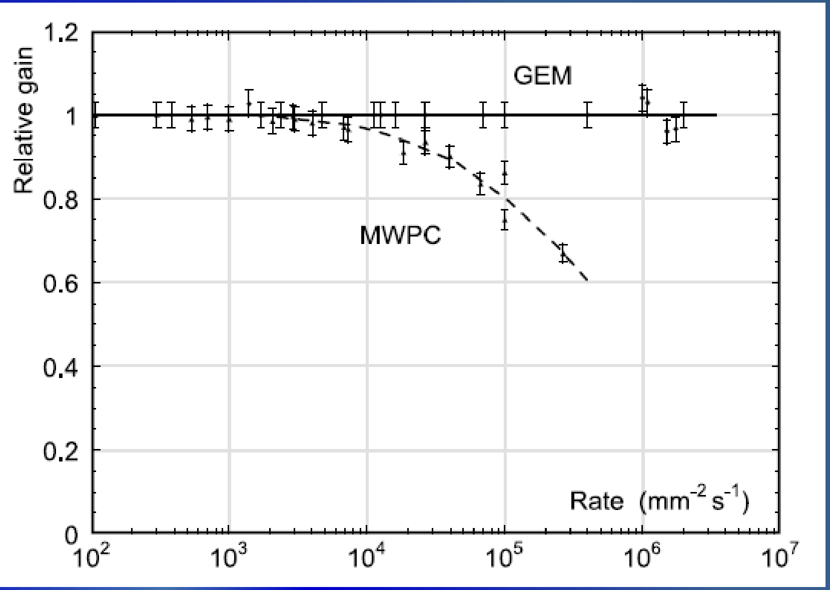


Micro-Pattern Gaseous Detector Technologies (MPGD)

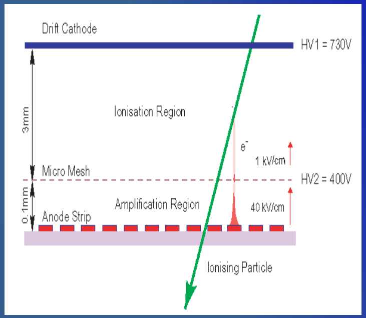
- ✓ *Micromegas*
- ✓ *Gas Electron Multiplier (GEM)*
- ✓ *Thick-GEM (LEM), Hole-Type & RETGEM*
- ✓ *MPDG with CMOS pixel ASICs ("GridPix")*

- ✓ *Micro-Pixel Chamber (μ–PIC)*
- ✓ *μ–Resistive WELL (μ-RWELL)*
- ✓ *Resistive-Plate WELL (RPWELL)*

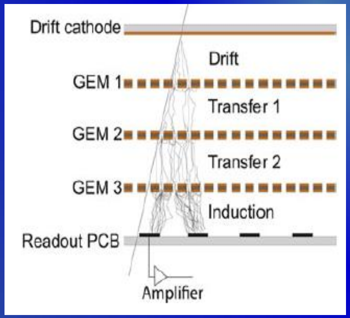
Rate Capability: MWPC vs GEM:



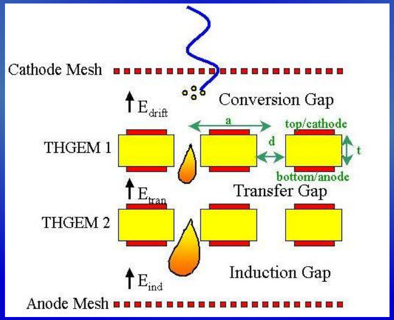
Micromegas

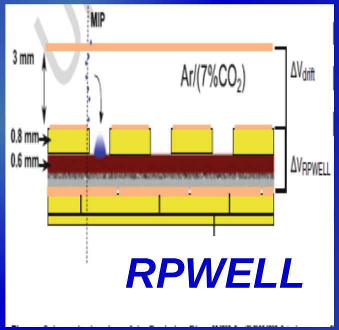


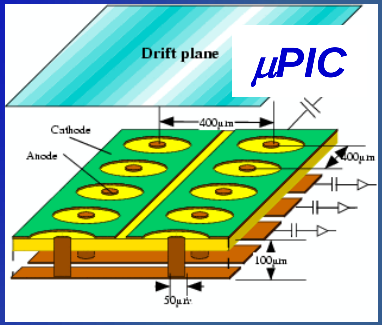
GEM

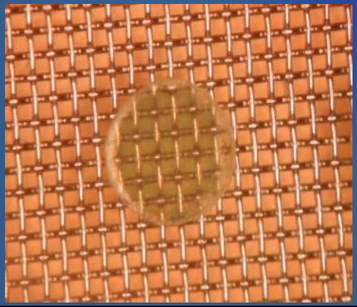


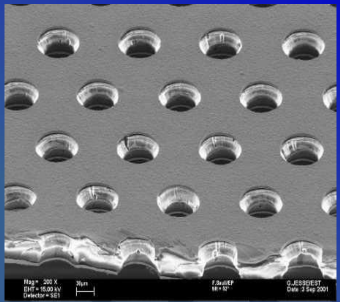
THGEM

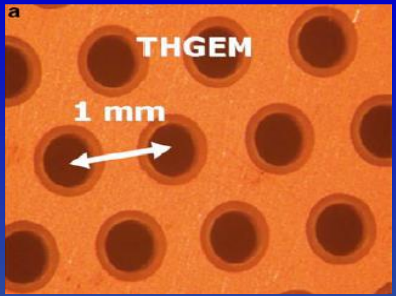


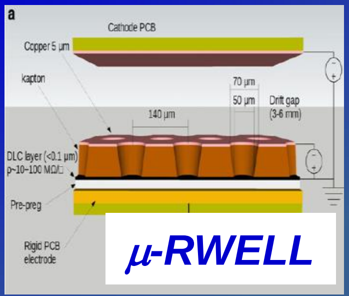


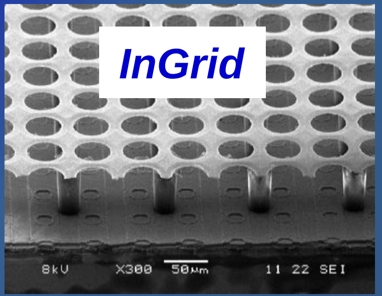










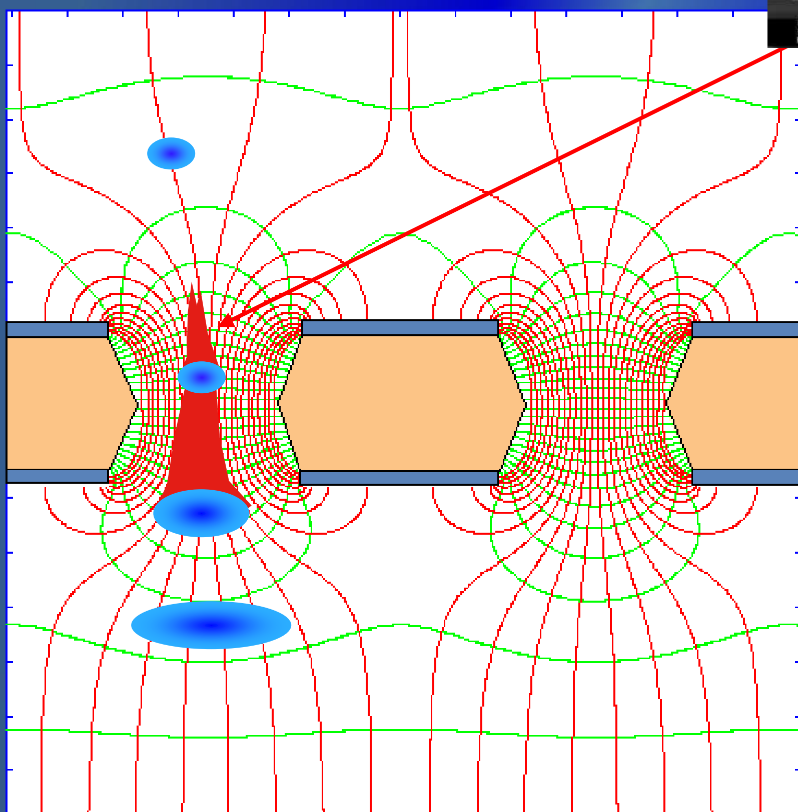


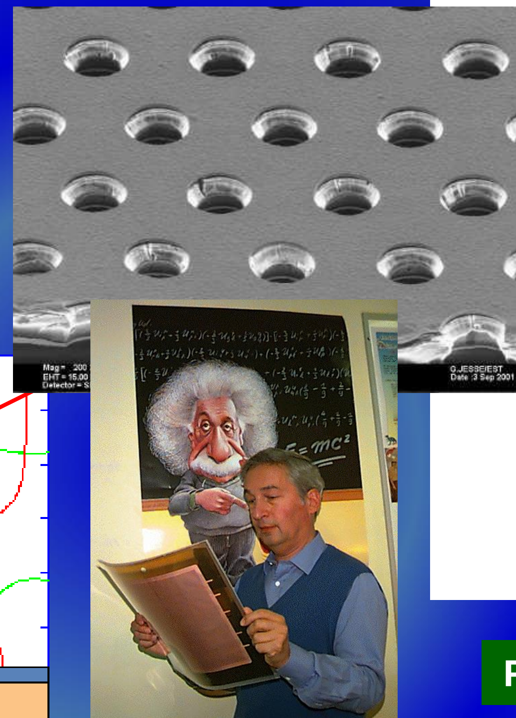
Gas Electron Multiplier (GEM)

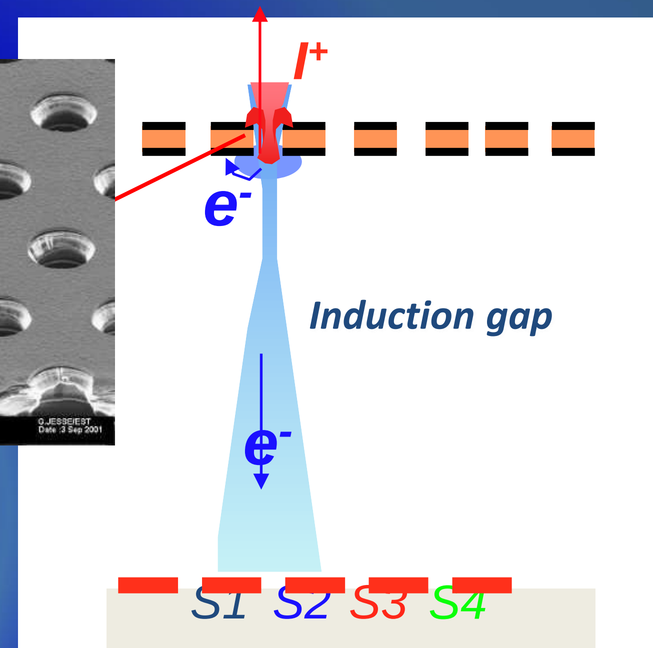
Thin metal-coated polymer foil chemically pierced by a high density of holes

A difference of potentials of ~ 500V is applied between the two GEM electrodes.

→ the primary electrons released by the ionizing particle, drift towards the holes where the high electric field triggers the electron multiplication process.







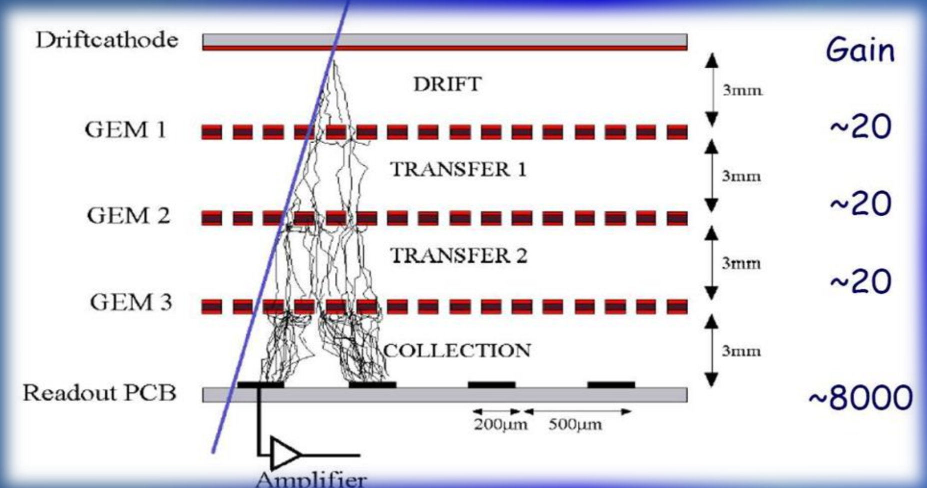
F. Sauli, NIMA386 (1997) 531

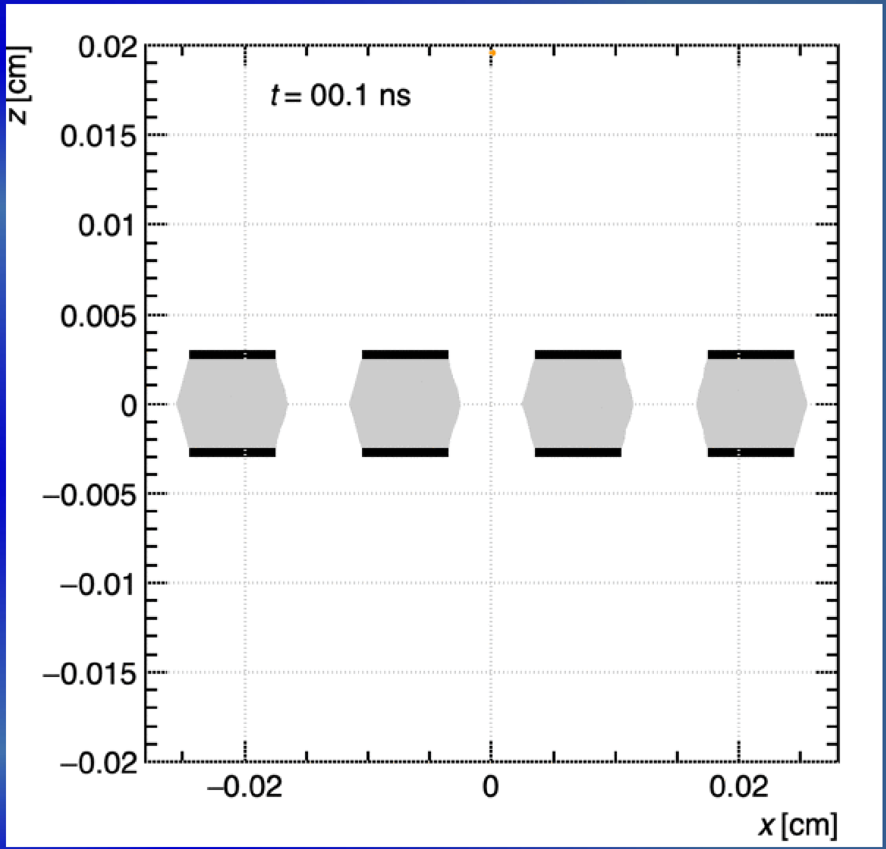
- ✓ Electrons are collected on patterned readout board.
- ✓ A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- ✓ All readout electrodes are at ground potential.
- ✓ Positive ions partially collected on GEM electrodes

Avalanche Simulation in GEM & Triple-GEM Structures

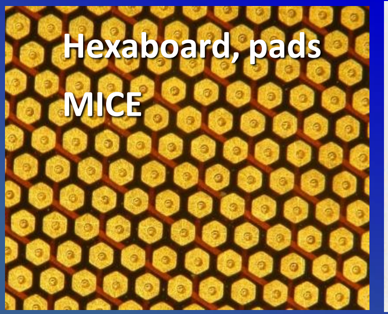
Animation of the avalanche process (Garfield++): *monitor in ns-time electron/ ion drifting and multiplication in GEM*

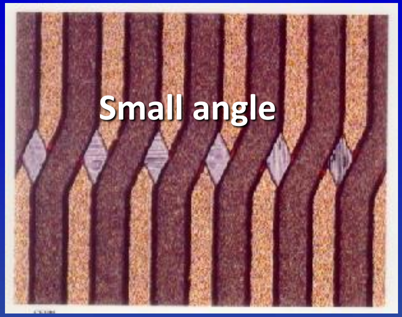
Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)

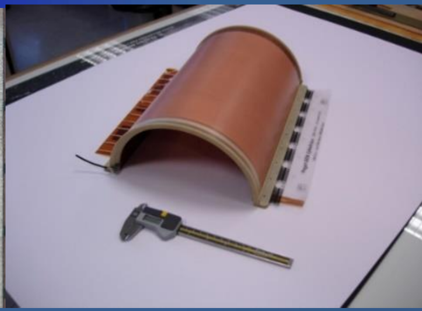




Amplification and readout structures can be optimized independently !



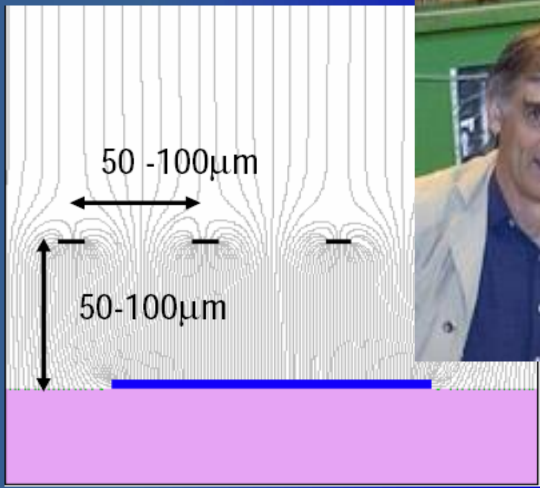


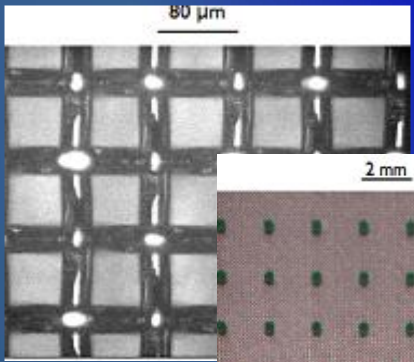


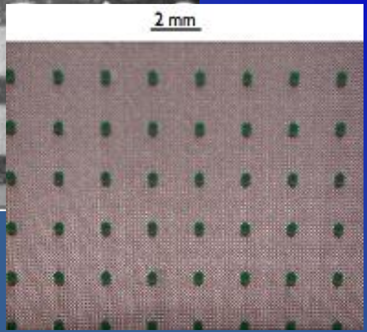
Micro Mesh Gaseous Structure (MICROMEGAS)

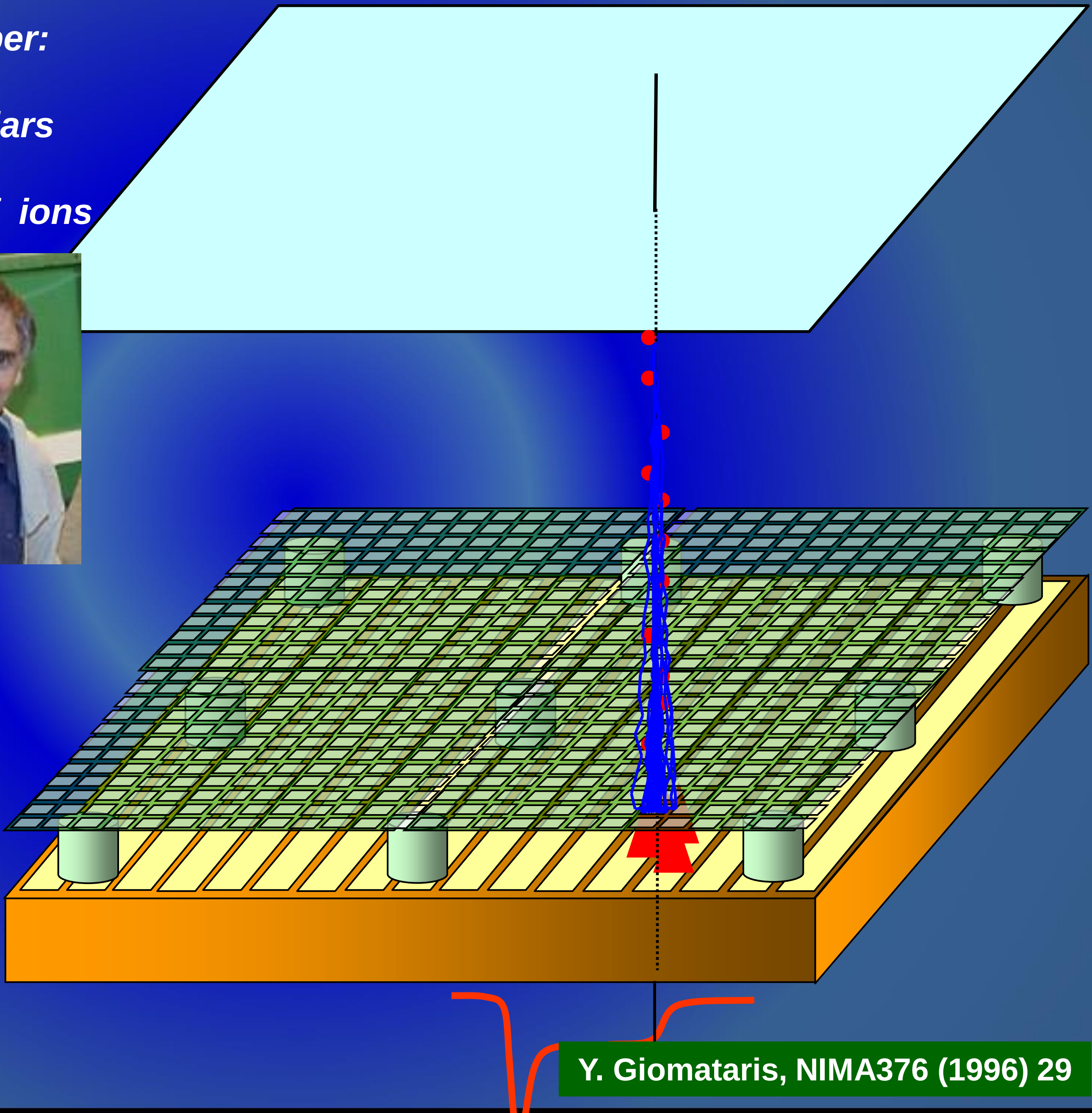
Micromesh Gaseous Chamber:
micromesh supported
by 50-100 mm insulating pillars

Small gap: fast collection of ions



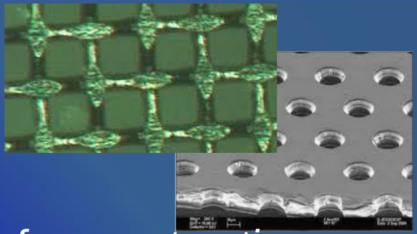




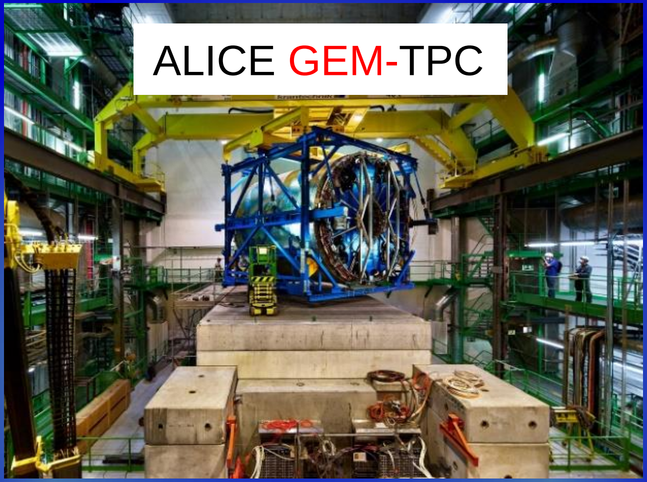


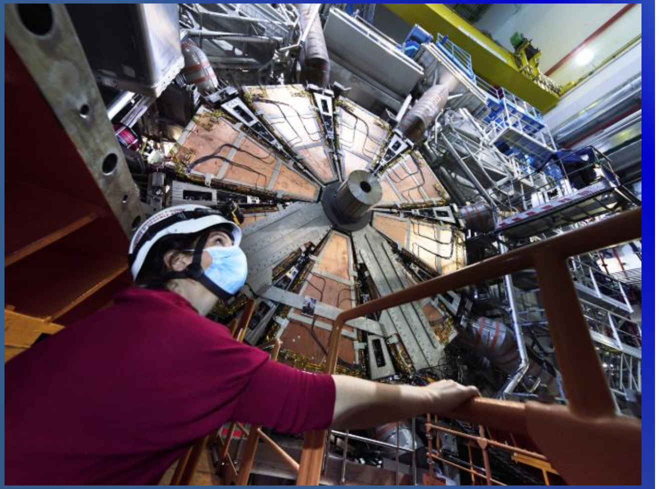
Y. Giomataris, NIMA376 (1996) 29

2022: MPGDs for High Luminosity LHC Upgrades



The <u>successful implementation of MPGDs for relevant upgrades of CERN</u> experiments indicates the degree of maturity of given detector technologies for constructing large-size detectors, the level of dissemination within the HEP community and their reliability





https://ep-news.web.cern.ch/content/atlas-new-small-wheel-upgrade-advances-0

https://ep-news.web.cern.ch/upgraded-alice-tpc

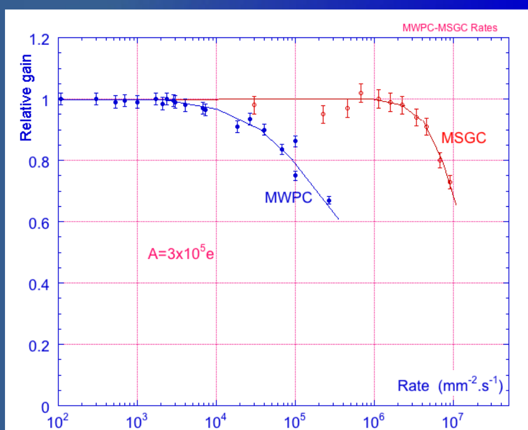
https://ep-news.web.cern.ch/content/demonstrating-capabilities-new-gem

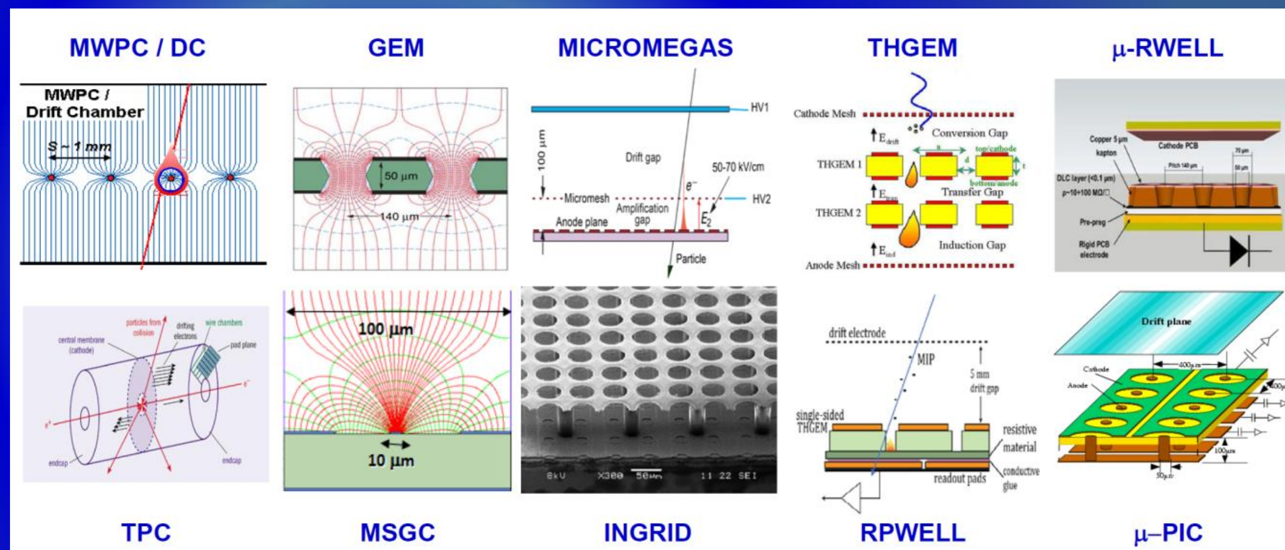
Gaseous Detectors: From Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

Primary choice for large-area coverage with low material-budget (+ dE/dx measurement)

1990’s: Industrial advances in photolithography has favoured the invention of novel micro-structured gas amplification devices (MSGC, GEM, Micromegas, …)

Rate Capability:
MWPC vs MSGC

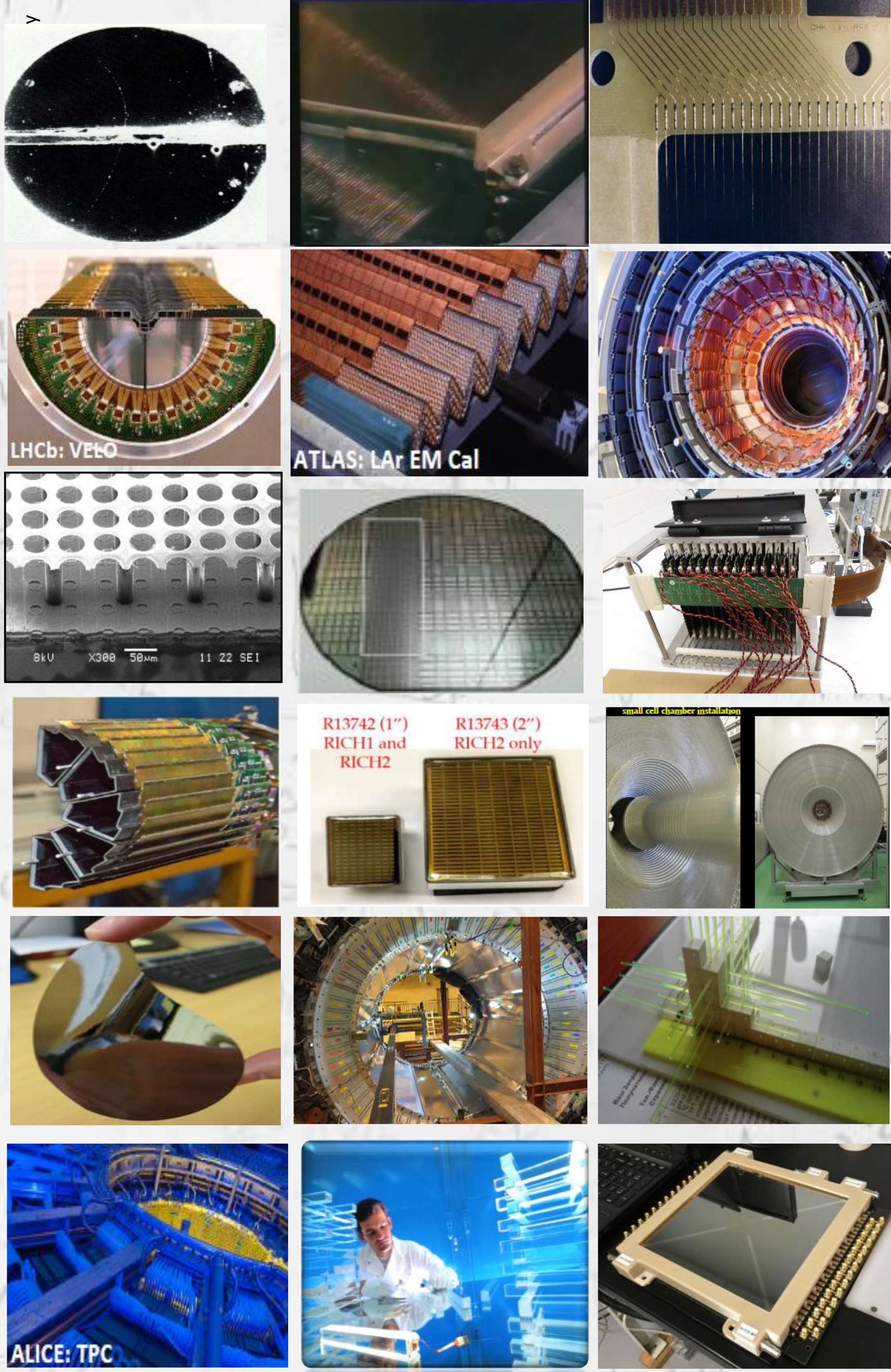




Examples of Gaseous Detectors for Future Colliders:

HL-LHC Upgrades: Tracking (ALICE TPC/MPGD); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;
Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, rates are comparable with HL-LHC)
Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (OK)

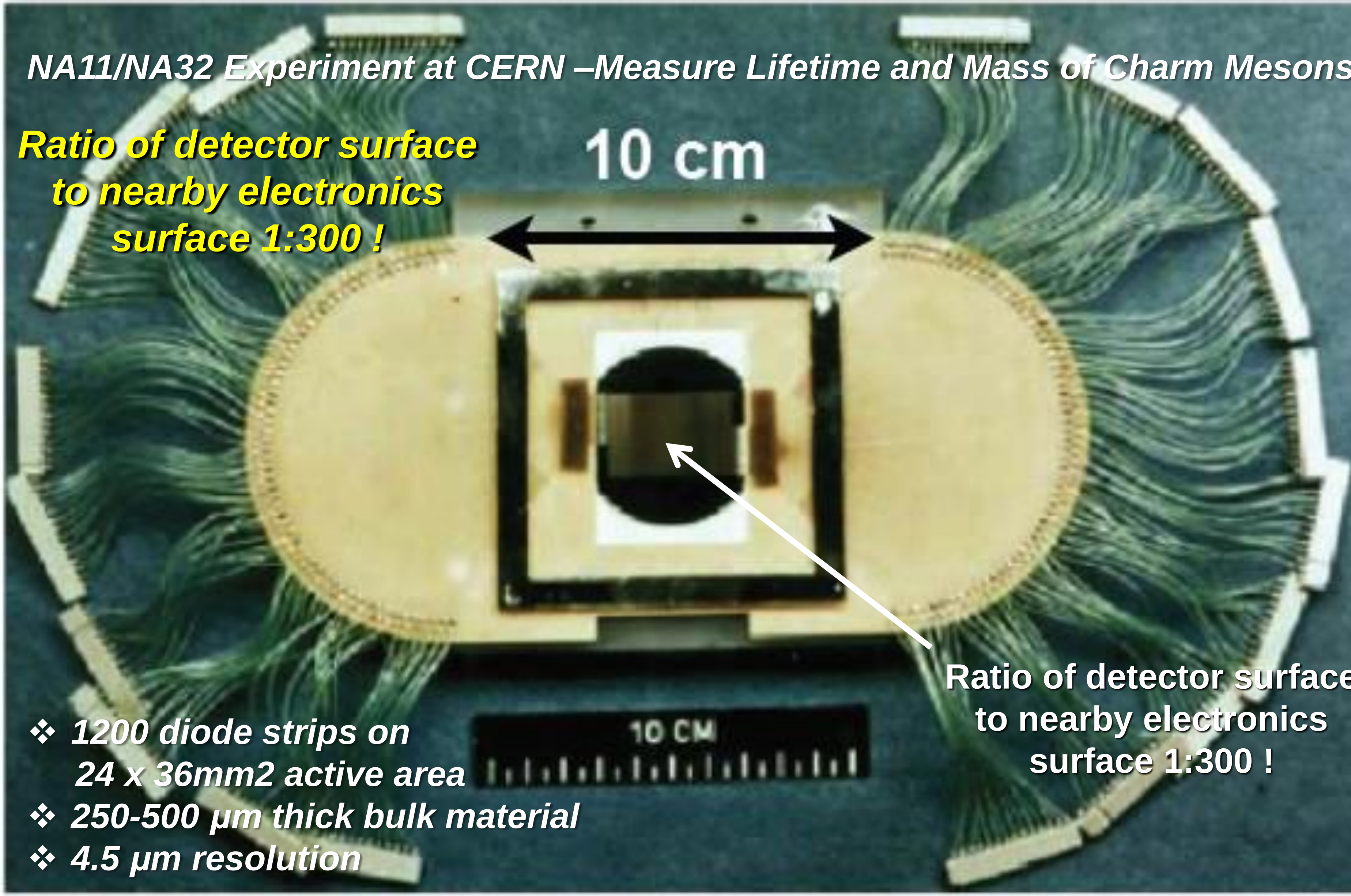
Future Election-Ion Collider: Tracking (GEM, μWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)



- Particle Interactions with Matter
- "Classic" Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

1983: First Silicon Strip Detector in Particle Physics

NA11/NA32 Experiment at CERN –Measure Lifetime and Mass of Charm Mesons



Ratio of detector surface to nearby electronics surface 1:300 !

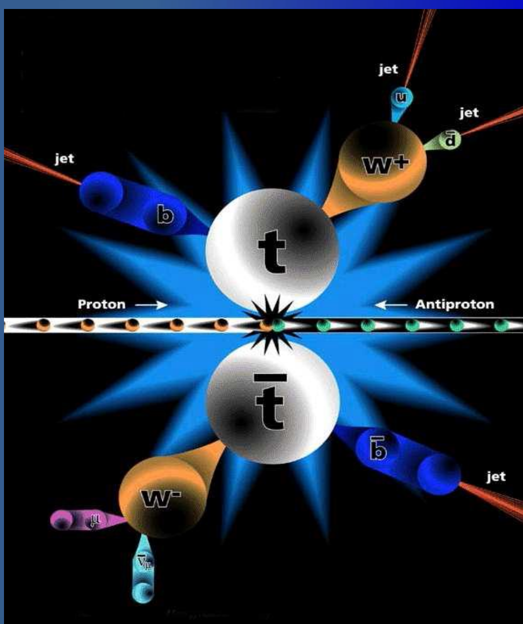
- *1200 diode strips on 24 x 36mm2 active area*
- *250-500 µm thick bulk material*
- *4.5 µm resolution*

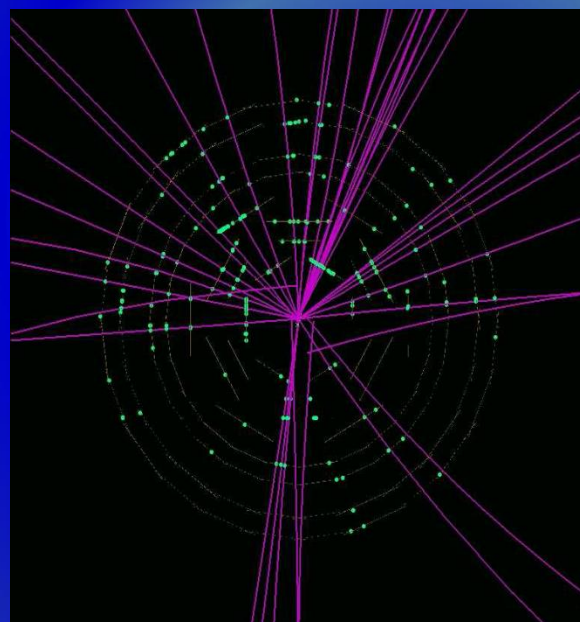
Ratio of detector surface to nearby electronics surface 1:300 !

Why Silicon Detectors: Discovery of Top Quark at Tevatron

1980's: The post era of the *Z and W discovery, after the observation of Jets at UA1 and* UA2 at CERN – "To proceed with high energy particle physics, one has to tag the flavour of the quarks!"

1995: Top Quark Discovery at Tevatron (t tbar → bW bbarW):





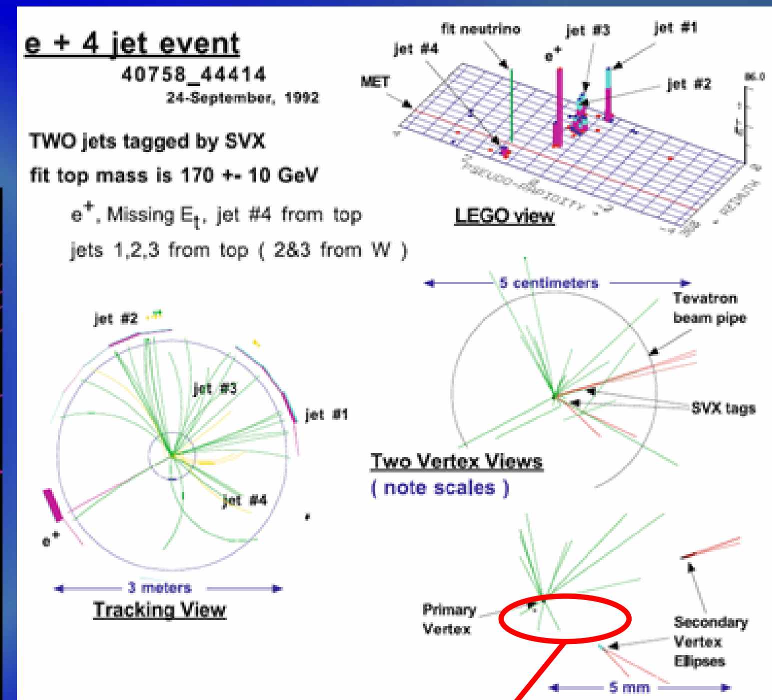
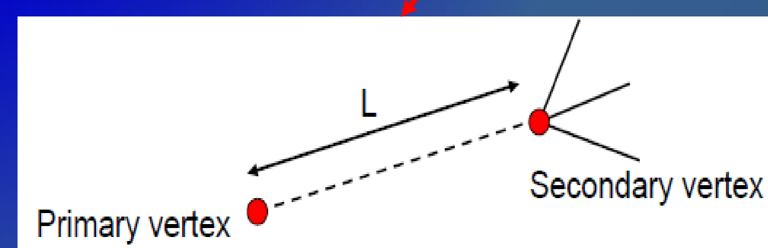


Fig. 4.23 A "Golden" t event. $t\bar{t}$ decaying into W^+b, $W^-\bar{b}$, where one W decays leptonically with the signature lepton ID plus missing energy, the second W decays into $q\bar{q}$ resulting in two jets together with the initial two tagged b jets. In total one lepton, four jets, two tagged b jets and missing energy were reconstructed [151]



Primary and secondary decay vertices → FIGURE OF MERIT: impact parameter

b-jet ID is crucial,making use of 1.5 ps b lifetime:
→ flight distance few 100 μm; hit precision ~ 10 μm

MAY 1995

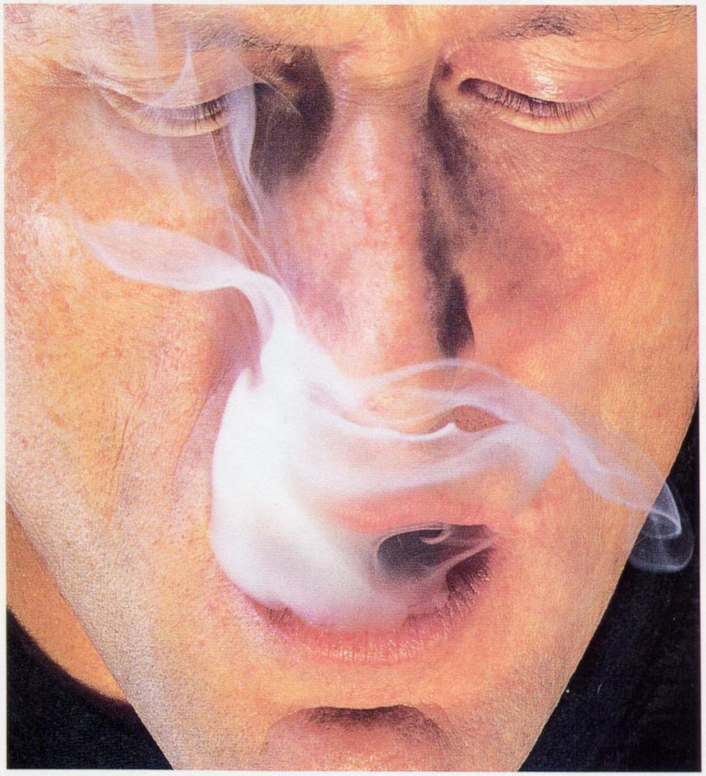
$3.95
U.K. £2.75

SCIENTIFIC AMERICAN

What found the top quark.

Archaeology in peril.

The Niels Bohr mysteries.



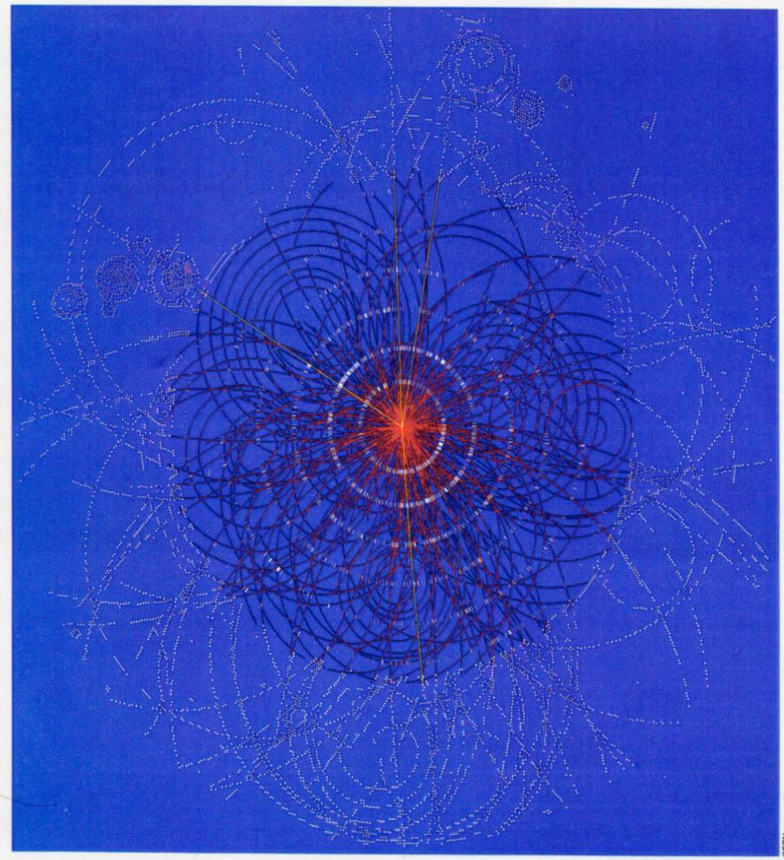
***Clouds** of tobacco smoke continue their spread, despite warnings.*

05>
9 770036 873022

The Silicon Microstrip Detector

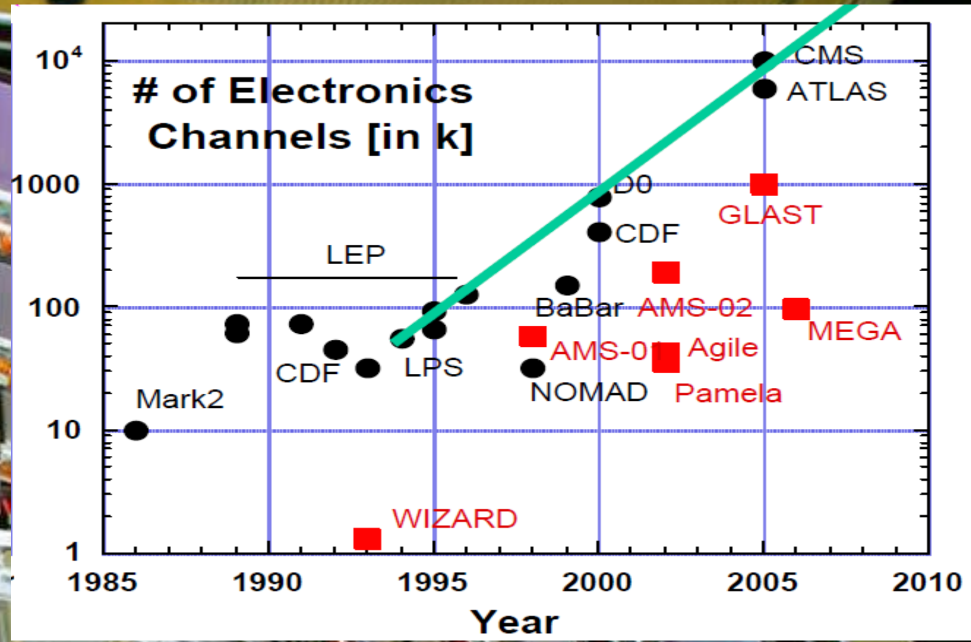
Produced with the same tools used to create integrated circuits, these detectors recently helped to find the top quark and are central to other crucial experiments

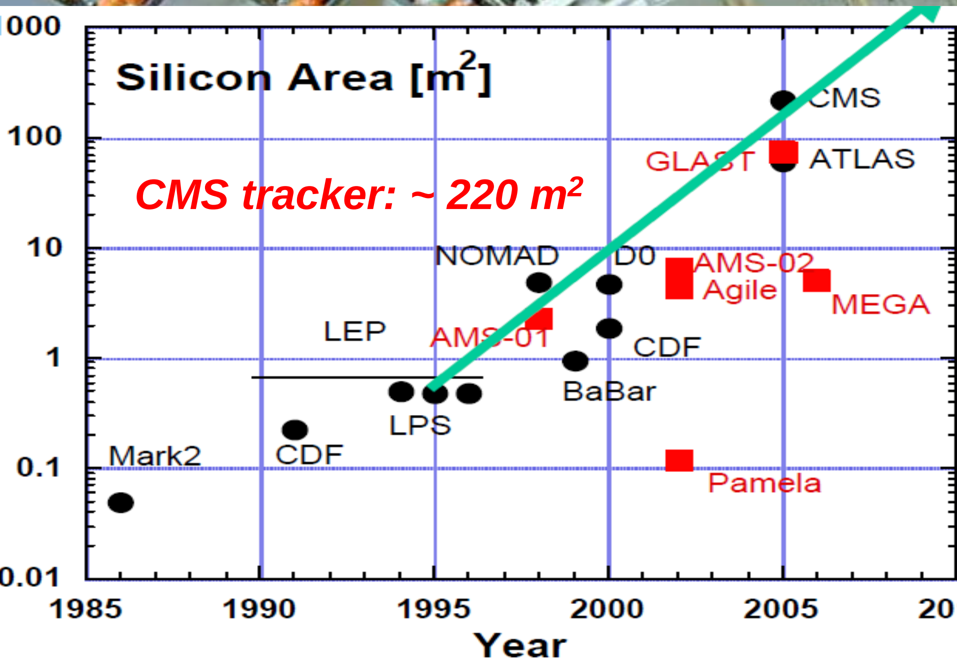
by Alan M. Litke and Andreas S. Schwarz

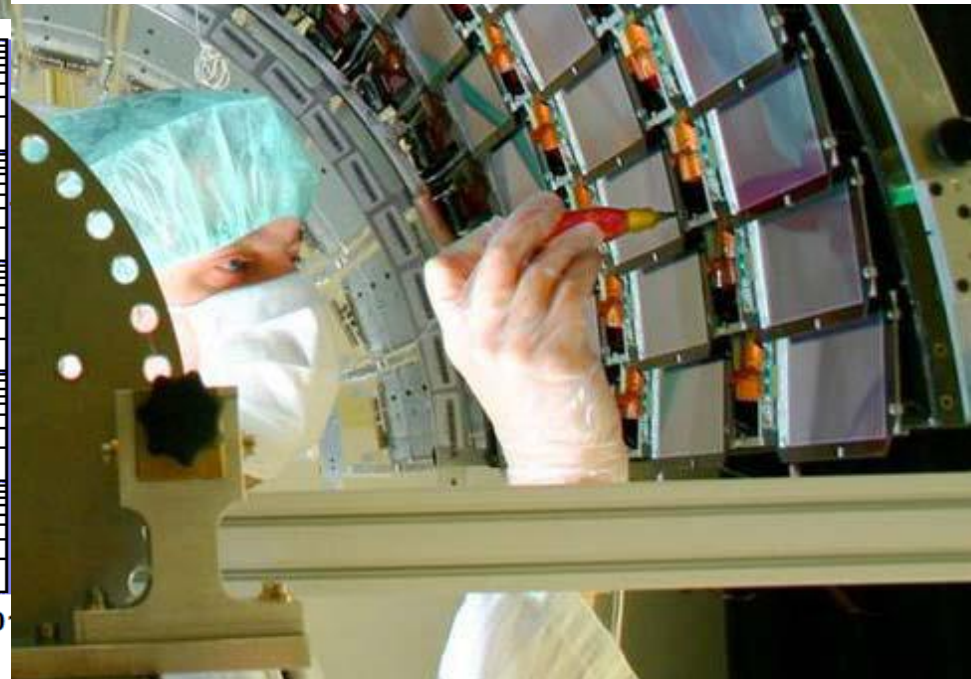


CERN

Silicon Detectors in Particle Physics: Evolution of Scale







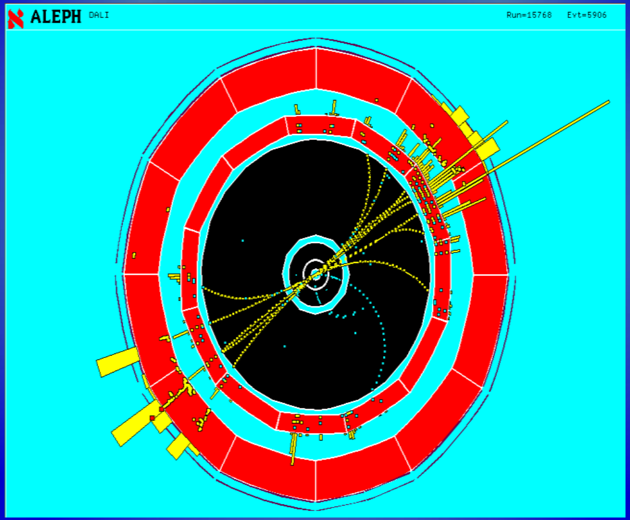
Silicon Detectors has Transformed the Way We Look at Particles

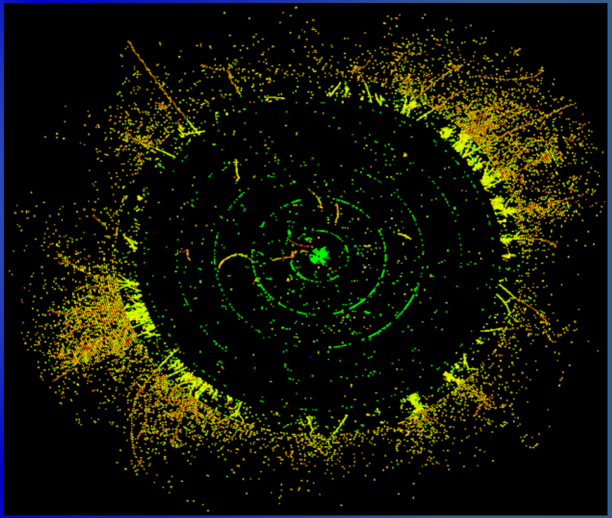
1950-1970: Pre-Silicon Era- photo of ionization trails

1990: Si-vertex detector & gaseous tracking (TPC)

2020: CMS / Higgs Factory
- *CMS HGCAL CALO*
- *ILC vertex/tracking/ calo*

It might look like we are actually seeing less now, but we can see a lot more than in pre-silicon era !





From Microelectronics to Nanoelectronics:
- *Particle Physics Detectors are more and more based on semiconductors;*
  → electronics feature size (65 nm), pixel detectors pitch 20 um

Enormous benefit (compared to gaseous detectors):
- *Huge technological advances of Si-technology in the IT industry*
- *Pattern and structure are industry standard (already using 10 nm feature size)*

Why Silicon For Tracking Detectors ?

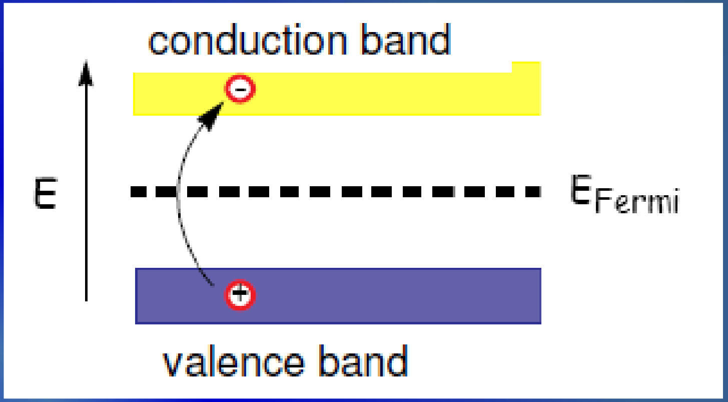
- ✓ *Low ionisation energy (few eV per e-hole pair) compared to gas detectors (20-40 eV per e-ion pair) or scintillators (400-1000 eV to create a photon)*
- ✓ *A condensed medium is obligatory for precision <10 microns (diffusion of electron cloud in gaseous detectors ~ tens of microns)*
- ✓ *Silicon band gap of 1.1 eV is 'just right'. Silicon delivers ~80 electron-hole pairs per micron of track, but kT at room temperature is only 0.026 eV, so dark current generation is modest*

Property		Si	Ge	GaAs	Diamant
Z		14	32	31/33	6
A		28.1	72.6	144.6	12.0
Band gap	[eV]	1.12	0.66	1.42	5.5
radiation length X_0	[cm]	9.4	2.3	2.3	18.8
mean energy to generate eh pair	[eV]	3.6	2.9	4.1	~ 13
mean E-loss dE/dx	[MeV/cm]	3.9	7.5	7.7	3.8
mean signal produced	$[e^-/\mu m]$	110	260	173	~ 50
intrinsic charge carrier concentration n_i	$[cm^{-3}]$	$1.5 \cdot 10^{10}$	$2.4 \cdot 10^{13}$	$1.8 \cdot 10^{6}$	$< 10^{3}$
electron mobility	$[cm^2/Vs]$	1500	3900	8500	1800
hole mobility	$[cm^2/Vs]$	450	1900	400	1200

Intrinsic Semiconductor: Basic Principles

- *Conduction band really empty at T = 0*
- *Probability for e- to occupy state given by Fermi-Dirac statistics:*

$$F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$



- *Probability of electron jumping from valence to conduction band is proportional to exp (-E_g/kT), where Eg is band gap energy (e.g. for intrinsic silicon E_g=1.1 eV, kT=1/40 eV at room temperature → it becomes a good conductor only at ~ 600 C)*

✓ *Electron from conduction band may recombine with holes*

✓ *A thermal equilibrium is reached between excitations and recombinations*

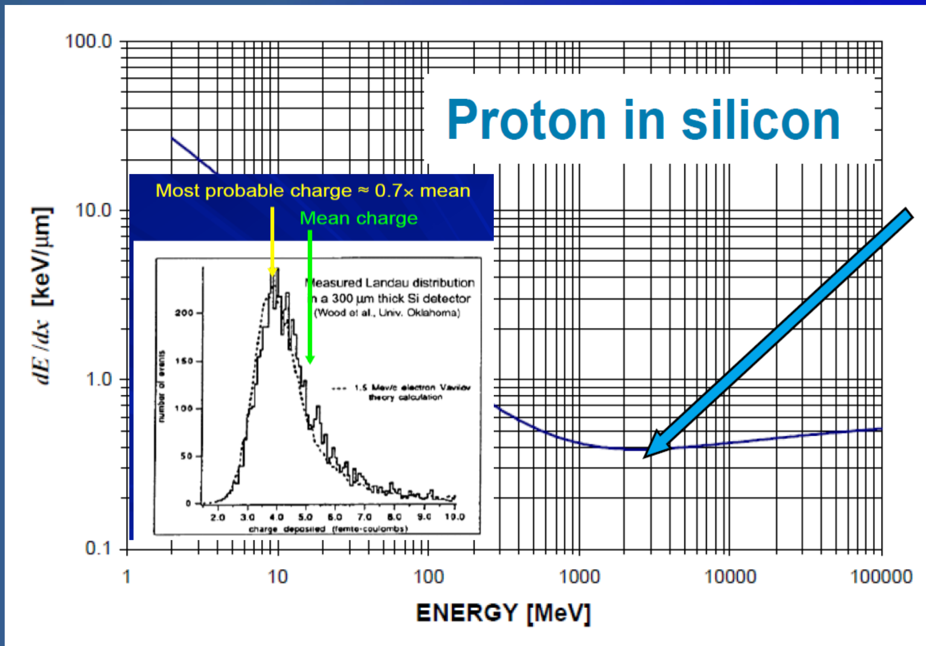
✓ *Charged carrier concentration $n_e = n_h = n_i$ (intrinsic carrier concentration):*

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

✓ *In ultrapure Si at room T the intrinsic carrier concentration is $1.45 \cdot 10^{10}$ cm^{-3} (with approximately 10^{22} Atoms/cm^3 about 1 in 10^{12} silicon atoms is ionized)*

Intrinsic Semiconductor: Constructing a Detector

Let's take a piece a Si and wait for a passing of charged ionizing particle



<u>*Signal of a MIP in d=300 um Si-detector:*</u>

dE/dx*d   3.87 MeV/cm * 0.03 cm
------------ = --------------------------------   ~ $3*10^4$
I_O 3.62 eV   (e/h p

- Fluctuations give the famous Landau distribution → the most probable value (22000 e/h pairs) is 0.7 of the peak

<u>*Intrinsic charge carrier in Si (in d = 300 um & area A = 1 cm²) at T = 300 K:*</u>

$n_i * d * A = 1.45 * 10^{10}\ cm^{-2} * 0.03\ cm * 1\ cm^2 \sim 4.35 * 10^8$ e/h pairs

Result: the number of thermal charge carriers (at room temperature) are <u>four orders of magnitude</u> larger than signal !!!

→ *Cool the solid-state detectots (n_i at 77K ~10^{-20}) → complicated*

→ *Deplete the volume from free charge carriers & to register MIP signal*

→ Reverse bias pn Junction

Creating a pn-Junction: Doping

- *Doping is the replacement of a small number of atoms in the lattice by atoms of neighboring columns from the atomic table (with one valence electron more or less compared to the basic material).*
  → Typical doping concentrations for Si detectors are ≈10^{12} atoms/cm^3 (10^{14} und 10^{18} atoms/cm^3 for CMOS elements).

- *These doping atoms create energy levels within the band gap and therefore alter the conductivity.*

Definitions:

- *An undoped semiconductor is called an intrinsic semiconductor*
  → In intrinsic semiconductor for each conduction electron there
- *exists the corresponding hole.*

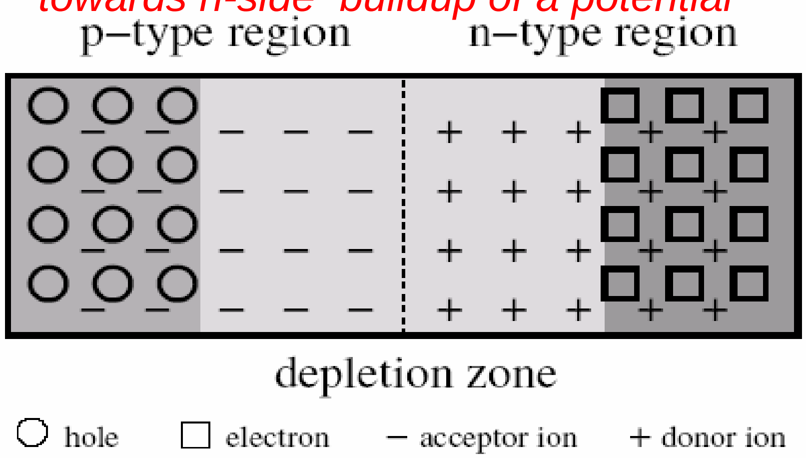
- *A doped semiconductor is called an extrinsic semiconductor*
  → in extrinsic semiconductor there is a surplus of electrons/holes.

Basic Principles: Creating pn-Junction

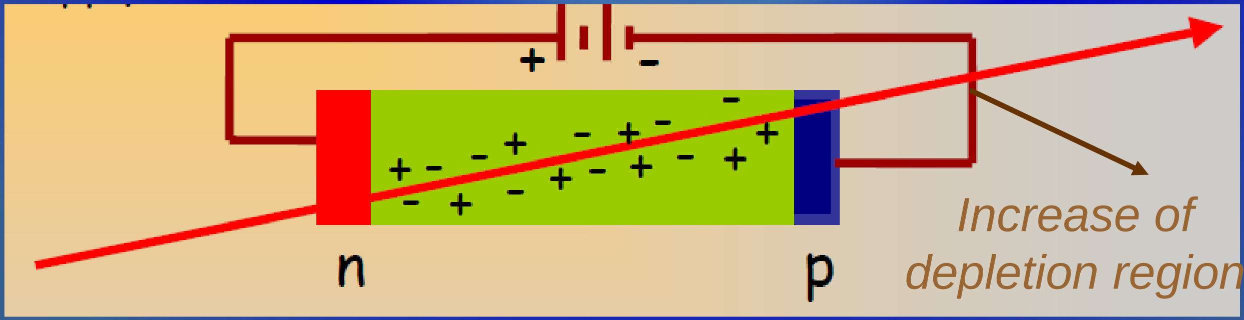
Now, for the magic part → we can construct pn junction

- *When brought together to form a junction, the majority diffuse carriers across the junction.*
- *The migration leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region.*
- *The electric field set up in the region prevents further migration of carriers.*

electrons drift towards p-side, holes towards n-side buildup of a potential



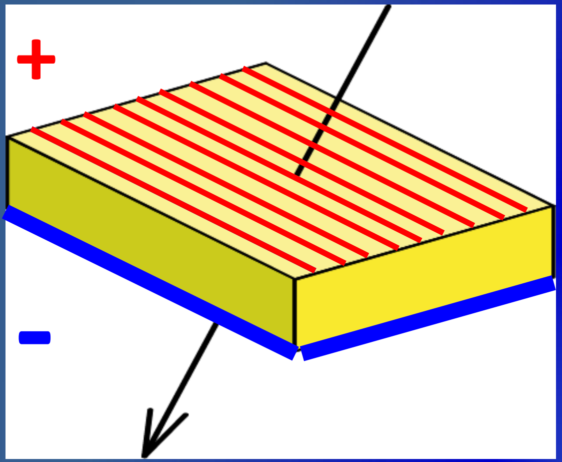
The depleted part is very nice, but very small → apply external voltage in the same direction as generated potential (reverse bias operation)



The depletion zone can be used as detector, since it contains an electric field (and is depleted of free charges).

Silicon Micro-Strip Detector: Basic Principles

- **Now take a large Si crystal, e.g. 10 x 10 cm², 300 µm thick**



make bottom layer p-type
and subdivide the top n-type layer int
→ many strips with small spacing

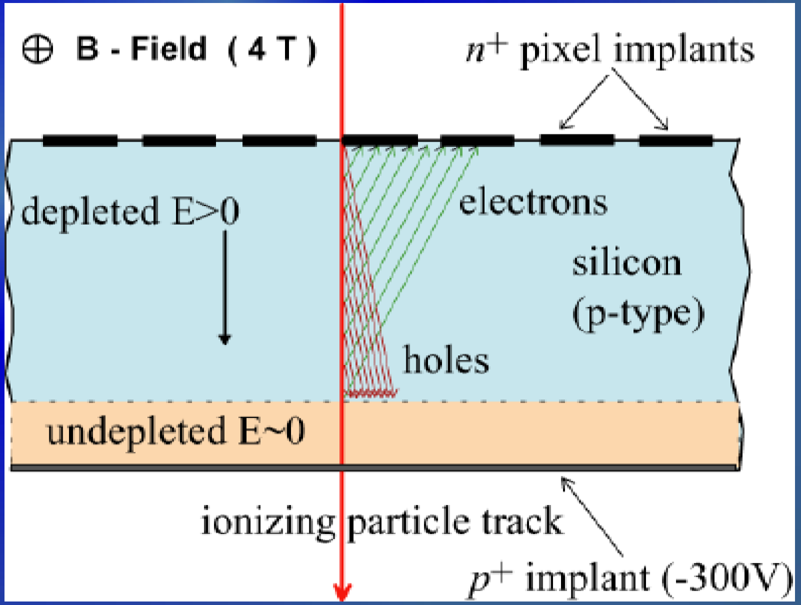
need many diodes next to each other & reverse bias to deplete entire sensor (like MWPC at wire chambers) with position information

- **Advantage compared to wire/gas detectors**

➔ **strip pitch can be rather high (e.g. ~20 µm)**

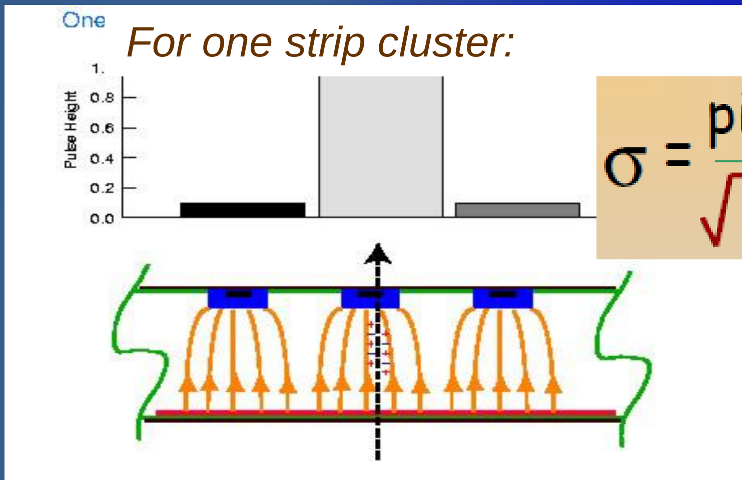
Sensors Design issues:

- *Thick ⇒ large signal*
- *Thin ⇒ less scattering*
- *Thin ⇒ lower depletion voltage*
- *Short strips ⇒less ambiguities*
- *Strips close ⇒ very precise measurement impact position*
- *Strips far apart ⇒ less electronics hence less expensive*

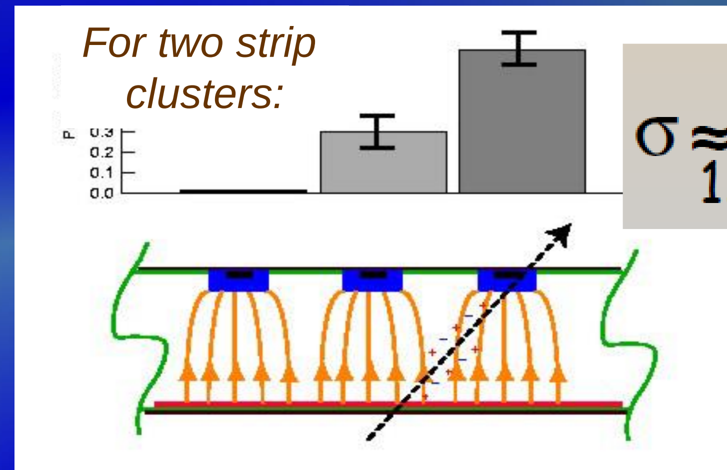


Silicon Micro-Strip Detector: Spatial Resolution

Resolution → difference between reconstructed position and true position



$$\sigma = \frac{pitch}{\sqrt{12}}$$

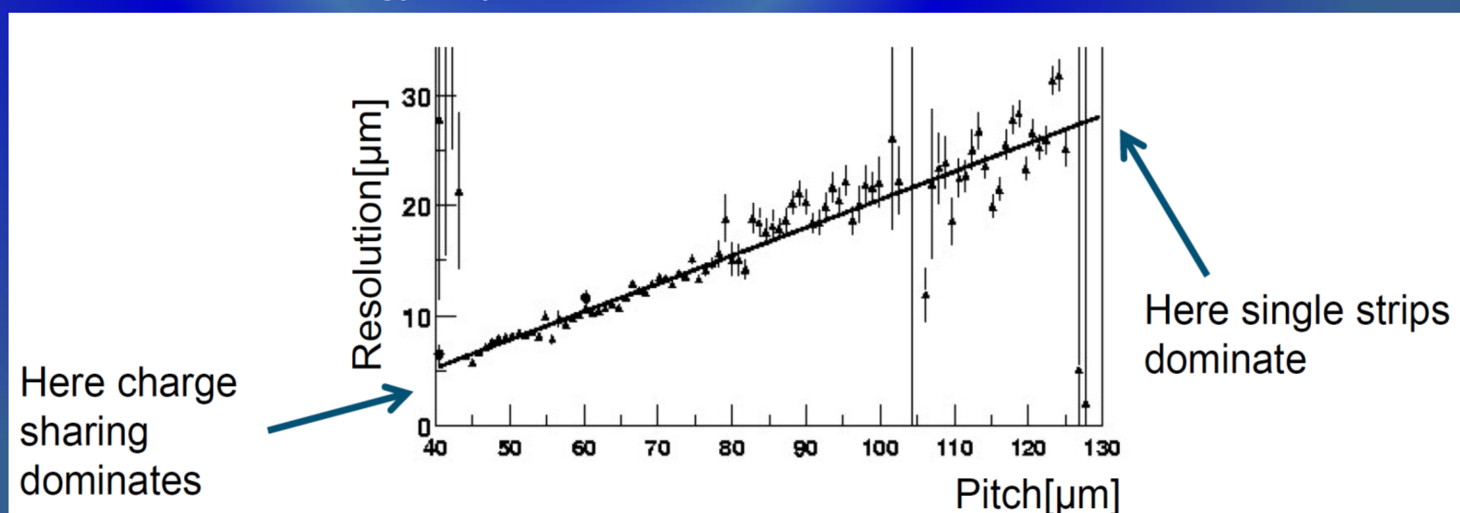


$$\sigma \approx \frac{pitch}{1.5 * (S/N)}$$

In real life, position resolution is degraded by many factors :

- Relationship of strip pitch and diffusion width (typically 25-150 um and 5-10 um)
- Statistical fluctuations on the energy deposition

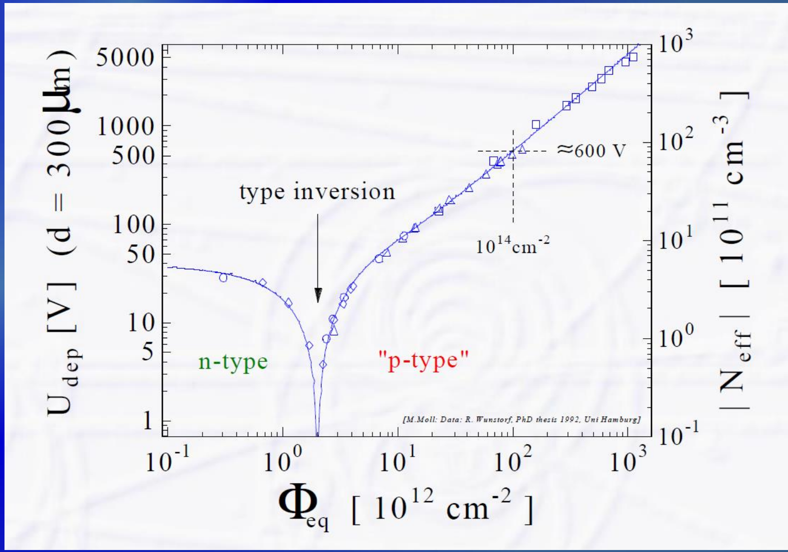
Typical values of 300 um thick sensor with S/N ~ 20:



Silicon Detectors: Radiation Damage

- **Solid state detectors suffer from radiation damage**
  - lots of R&D effort was spent over the past years to understand and to develop radiation-hard Si-detectors that can survive 10 LHC years

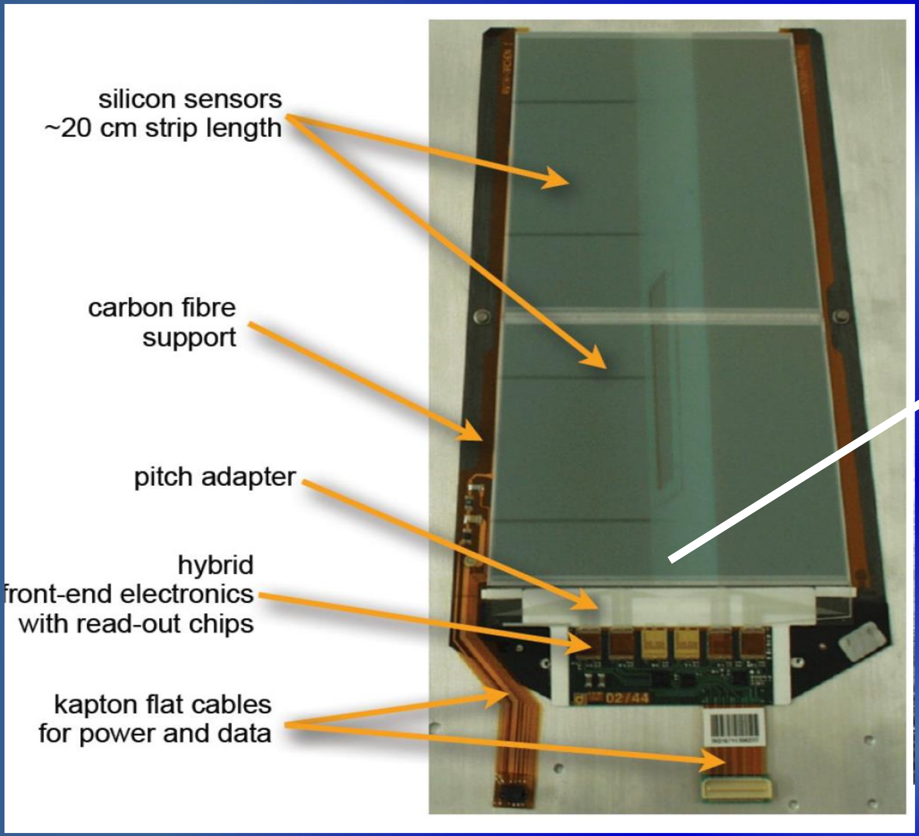
- **Two general types of radiation damage**
  - **bulk (crystal) damage** (mainly by nuclear interactions of protons/neutrons
    - change of depletion voltage
      - up to "type inversion"
      - n-type material becomes p-type material
    - increase of leakage current
      - higher noise, more cooling needed
    - decrease of charge collection efficiency
      - less signal
  - **surface damage**
    - accumulation of positive ions on surface insulating structures (oxides)
      - higher noise, breakdown

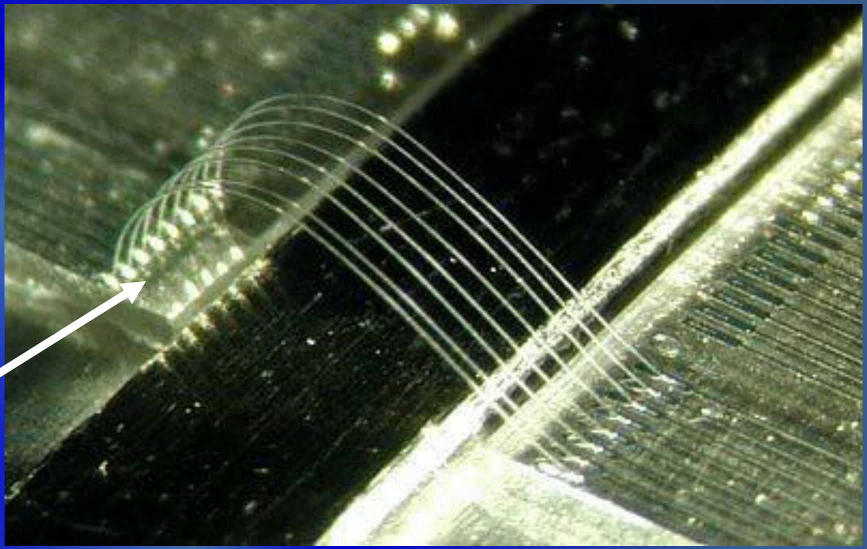


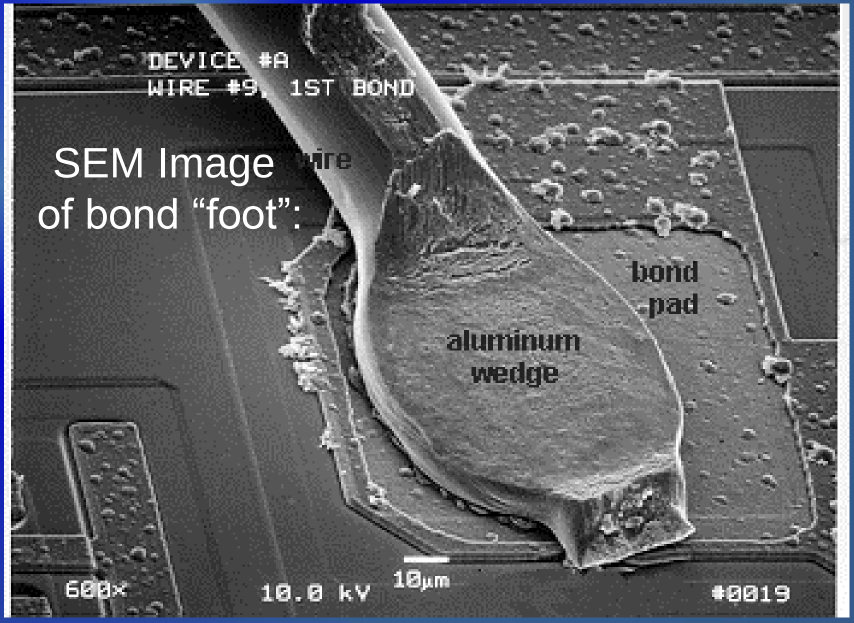
"Type inversion:
n-type materialchanges to p-type material after a certain accumulated radiation dose

CMS Silicon-Strip module: FEE and Connectivity

Wire bonding – A "mature" technology (has been around for 40 years) →
the standard method for connecting sensors to each other and to the front-end chips.





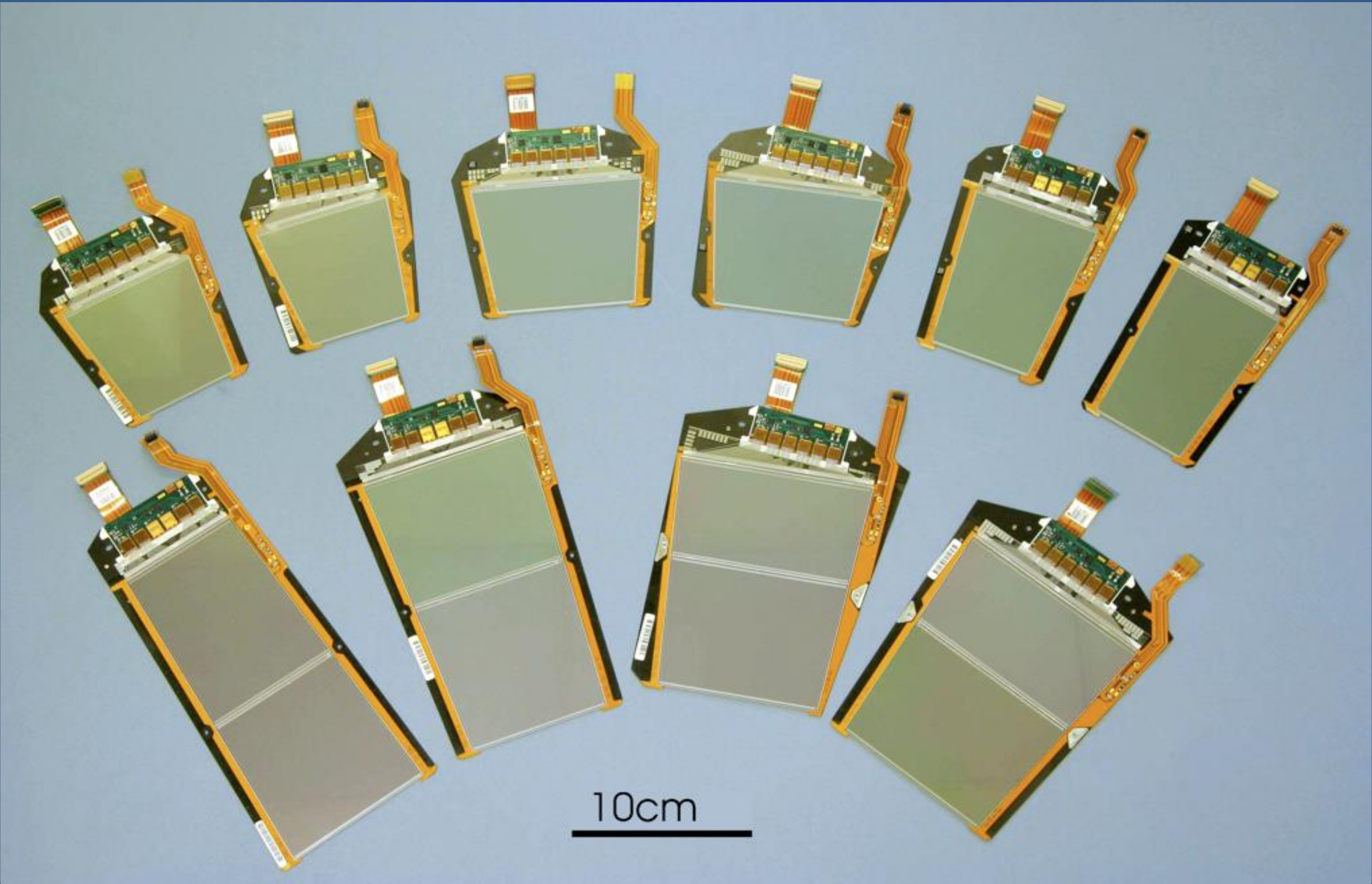


• Uses ultrasonic power to vibrate needle-like tool on top of wire (17-25 um Al wire). Friction welds wire to metalized substrate underneath.

• Heavily used in industry (PC processors) but not with such thin wire or small pitch.

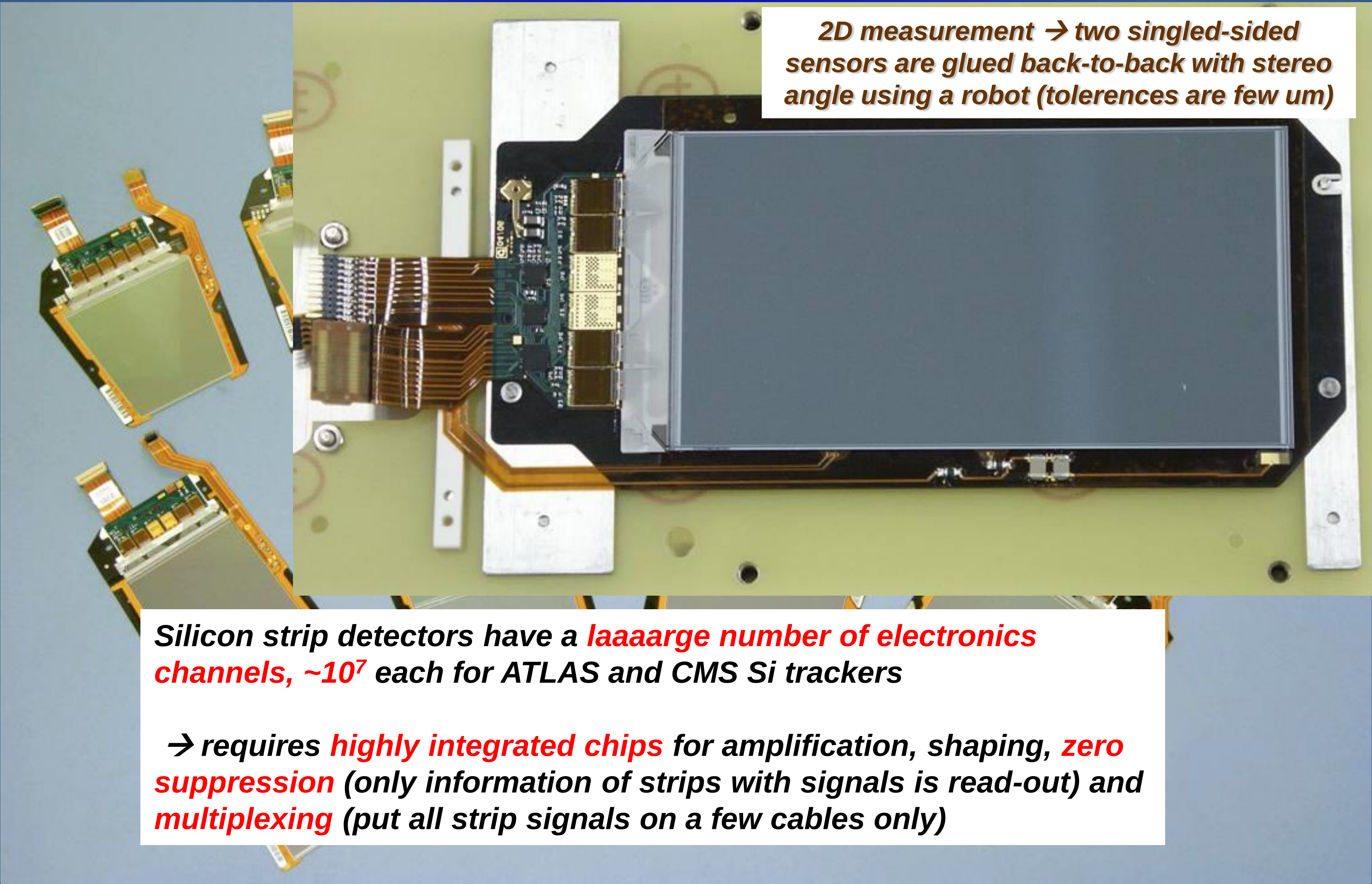
Examples of CMS Silicon Strip Modules

27 mechanical different modules + 2 types of alignment modules



Examples of CMS Silicon Strip Modules

27 mechanical different modules + 2 types of alignment modules



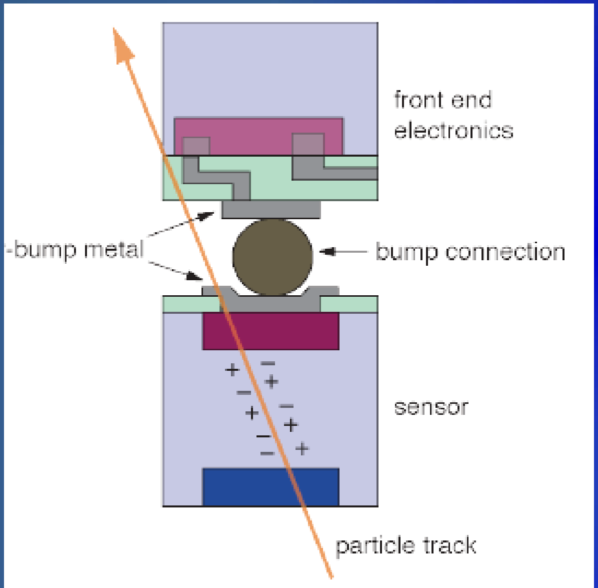
2D measurement → two singled-sided sensors are glued back-to-back with stereo angle using a robot (tolerences are few um)

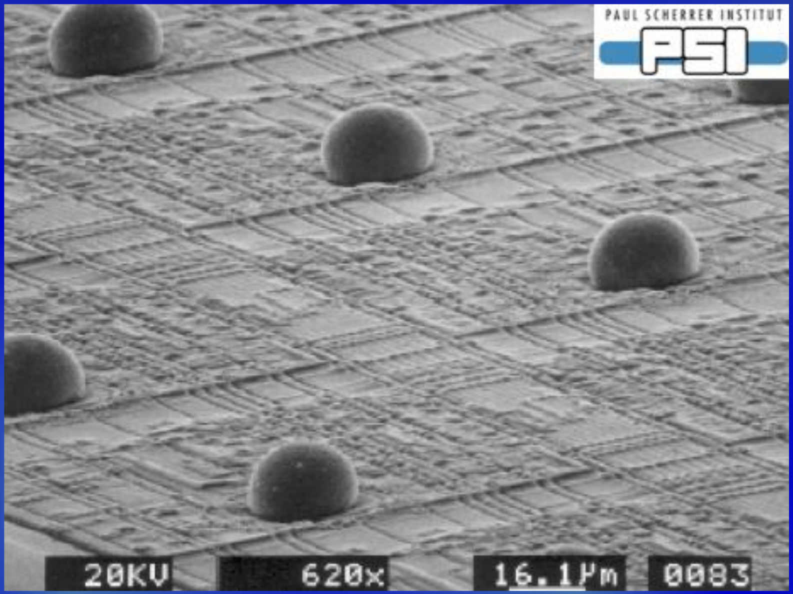
Silicon strip detectors have a laaaarge number of electronics channels, ~10^7 each for ATLAS and CMS Si trackers

→ requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)

Hybrid Pixel Detector

Details of the bump-bond connection:
Bottom is the detector, on top the readout chip





Bonds:
- *50 mm pitch*
- *PbSn or In*
- *6-20 mm high*
- *~ 3000/chip*
- *~50000/module*

Bump-bond failure rate (CMS) ~ 10^{-4}

Sensor Tech. in LHC Experiments:

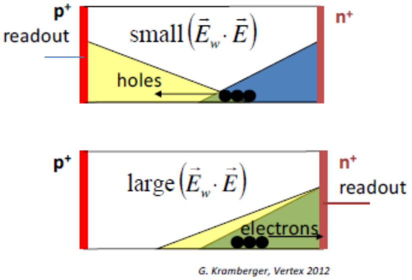
Main ingredients required for first (hybird) silicon pixel detectors (after planar process allowed to produce pixel sensors):

✓ VLSI (Very Large Scale Integration) technology to produce complex ASICs (Application Specific Integrated Circuit) – Hybrid, Monolithic

✓ Interconnect technology based on flip-chip bonding (connections of ~20µm between each sensor pixel cell and corresponding readout cell in an ASIC) - Hybrid

- p-in-n, n-in-p (**single sided process**)
- n-in-n (**double sided process**)
- Choice of sensor technology mainly driven by the **radiation environment**

	Fluence 1MeV n_{eq} [cm^{-2}]	**Sensor type**
ATLAS Pixel*	1 x 10^{15}	n-in-n
ATLAS Strips	2 x 10^{14}	p-in-n
CMS Pixels	3 x 10^{15}	n-in-n
CMS Strips	1.6 x 10^{14}	p-in-n
LHCb VELO	1.3 x 10^{14}**	n-in-n, n-in-p
ALICE Pixel	1 x 10^{13}	p-in-n
ALICE Drift	1.5 x 10^{12}	p-in-n
ALICE Strips	1.5 x 10^{12}	p-in-n



n-side readout (n-in-n, n-in-p) after inversion:
- Depletion from segmented side (under-depleted operation possible)
- Electron collection
- Favorable combination of weighting field and
- Natural for p-type material

Ultra Radiation Hard 3D Detectors: Concept

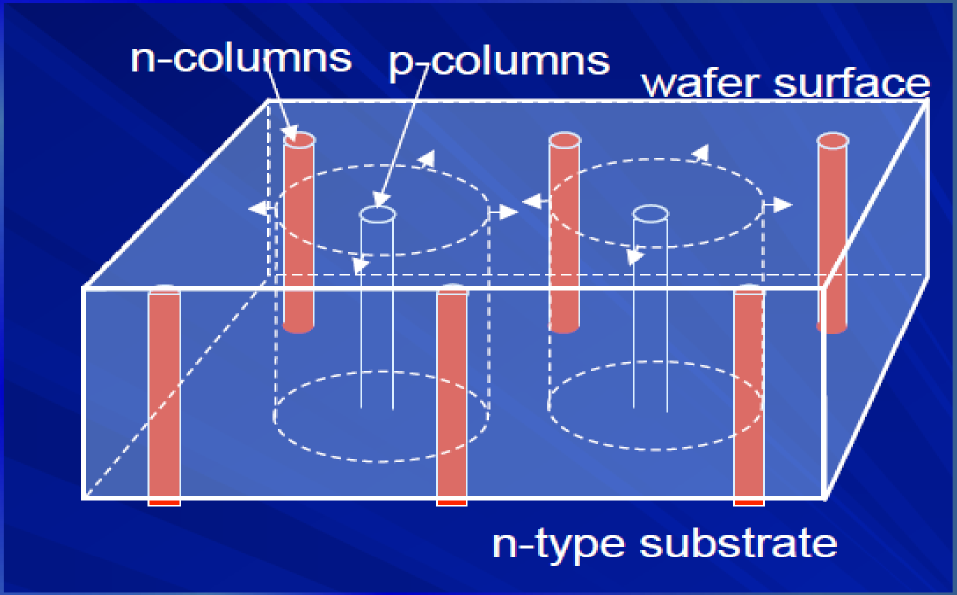
Maximum drift and depletion distance set by electrode spacing:

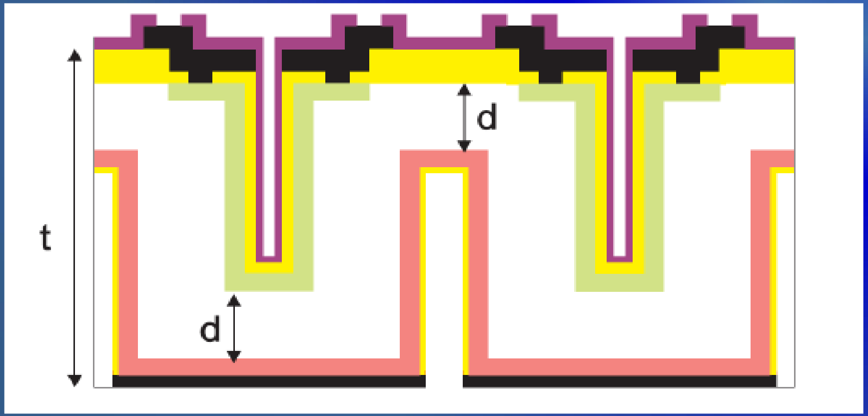
- *Lower depletion voltages*
- *Faster/more efficient charge collection*
- *Small leakage currents*
- *Very good performance at high fluences*
- *Narrow dead regions at the edges*

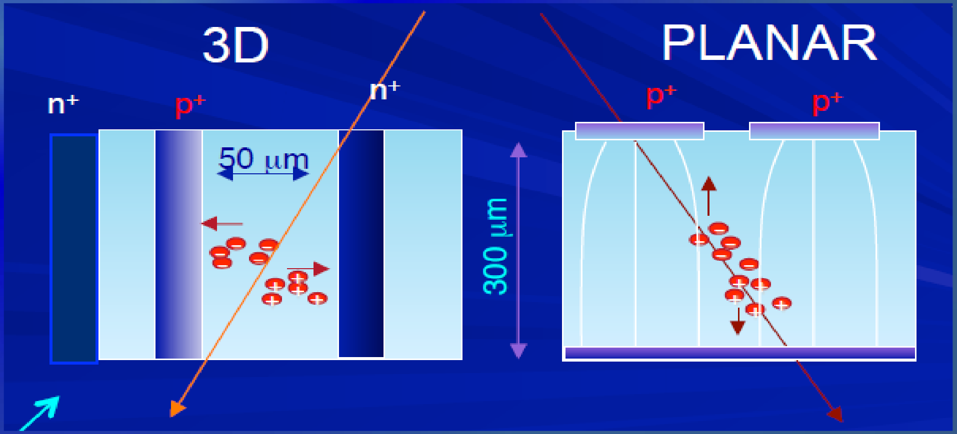
Production time and complexity for larger scale production

Used in ATLAS IBL

Both electrodes types are processed inside detector bulk
hole diameter: 10 mm; distance ~20-50 mm



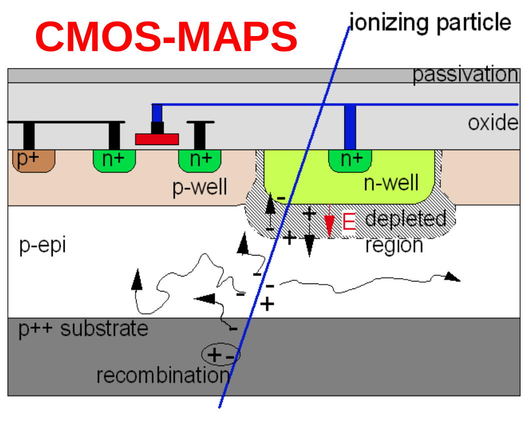




Emergence Of Monolithic Detectors: CMOS MAPS

Monolithic Active Pixel Sensors (MAPS):

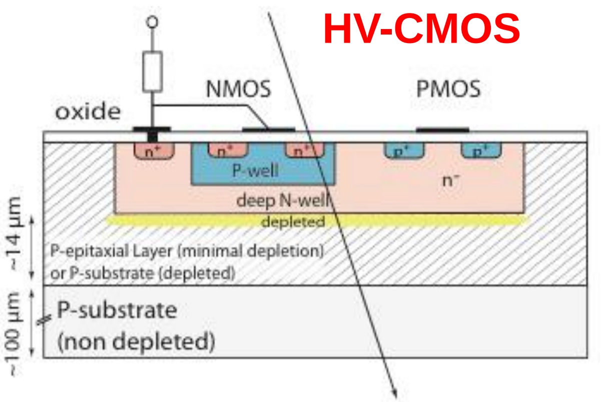
- *Commercial standard CMOS industrial process - low cost;*
- *Small pixels sizes ≃ 25 x 25 μm^2 ; thin sensors ~ 50 - 100 μm;*
- *Typical signal ~ 1000e on n-well contacts, low noise ~ 20e;*
- *Charge generation volume integrated into the ASIC*
  → no chip bump-bonding;
- *Charge collection mainly by diffusion → spread;*
  timing limited by rolling-shutter r/o (ms);



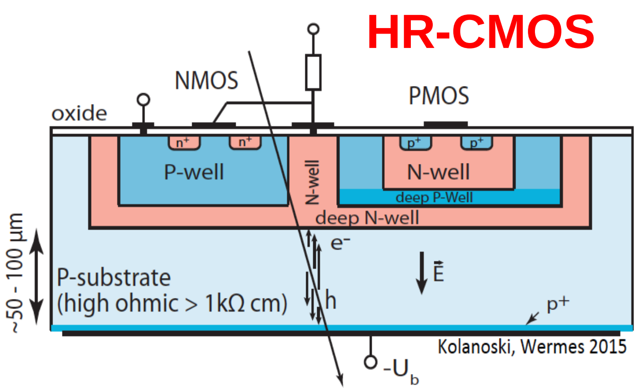
Charge generation volume is integrated into the ASIC

Monolithic Active Pixel Sensors (MAPS) with depletion

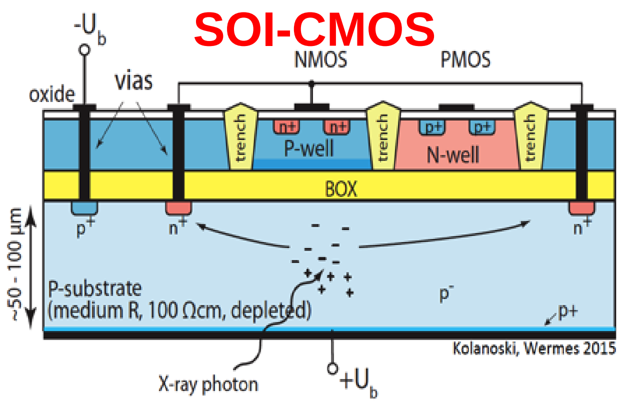
- *HV/HR-CMOS process electronics in deep n-well to allow bias for partial/full depletion or SOI process (vias through insulator to isolate bias from electronics)*



HV process, 10 - 15 um depletion region under deep N-well



HR process - can be fully depleted



SOI process fully depleted or HV process

Vertex Technologies for Future Linear Colliders (ILC)

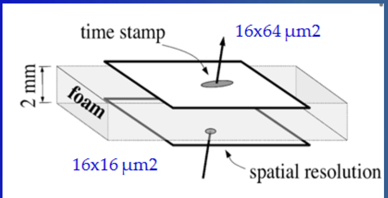
- **Sensor's contribution to the total X_0 is 15-30% (majority cables + cooling + support)**
- **Readout strategies exploiting the ILC low duty cycle 0(10^{-3}): triggerless readout, power-pulsing**
  - → continuous during the train with power cycling → mechanic. stress from Lorentz forces in B-field
  - → delayed after the train → either ~5μm pitch for occupancy or in-pixel time-stamping

Physics driven requirements — **Running constraints** — **Sensor specifications**

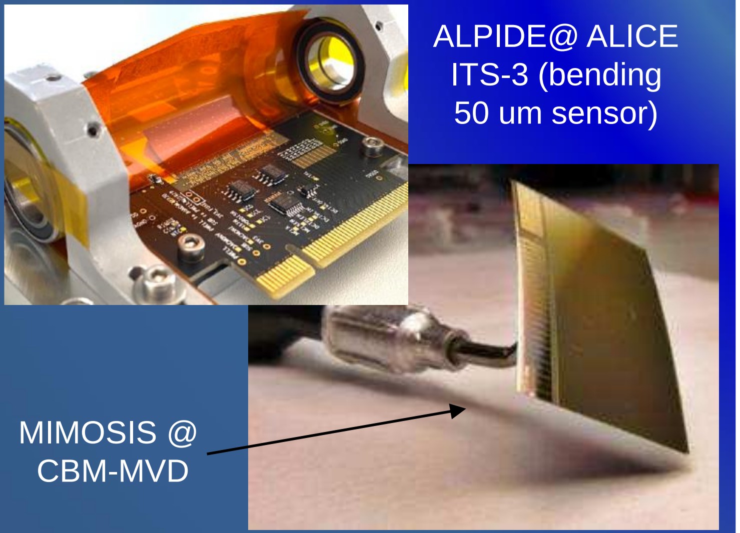
- $\sigma_{s.p.}$ 2.8um → Small pixel ~16 μm
- Material budget 0.15% X_0/layer → Thinning to 50 μm
- → Air cooling → low power 50 mW/cm²
- r of Inner most layer 16mm → beam-related background → fast readout ~1 μs
- → radiation damage → radiation tolerance ≤3.4 Mrad/year, ≤6.2×10¹² n_{eq}/(cm² year)

Technology	FPCCD	DEPFET	SOI	CMOS	iLGAD
Added value (example)	Very granular	Low material budget	2 tier process (high density μcircuits)	Industry evolution	PID

CMOS (MAPS): 2-sided ladders: « mini-vectors » concept for ILC with high spatial resolution & time stamping



180 nm CMOS technology: VALIDATED



ALPIDE@ ALICE ITS-3 (bending 50 um sensor)

MIMOSIS @ CBM-MVD

ALICE-ITS3 upgrade drives the R&D:

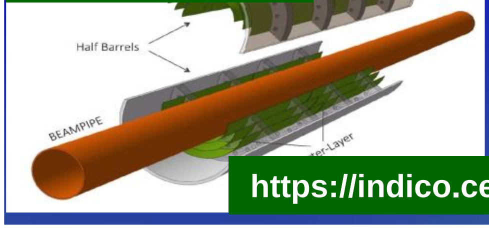
Bending thin Si-layers (MAPS):

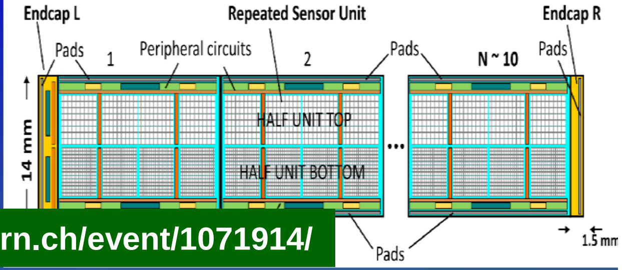
Truly cylindrical, supportless CPS for ALICE-ITS3 upgrade (65 nm)

Industrial stitching & large surfaces for low-mass detect.:

using several reticles from the same wafer (possible with both 180 and 65 nm)

arXiv: 2105.13000



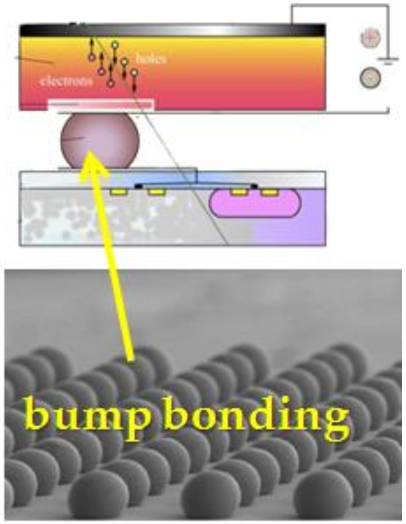


https://indico.cern.ch/event/1071914/

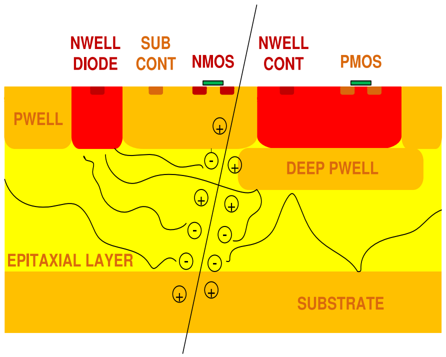
Solid State Tracking: Detector – Electronics Integration Trends

- ✓ *Radiation hardness improvements demand newer technologies*
- ✓ *Improved functionality can only be achieved with higher integration*
- ✓ *Power dissipation and material budget must be reduced*

TODAY: Pixels
50 – 100s μm

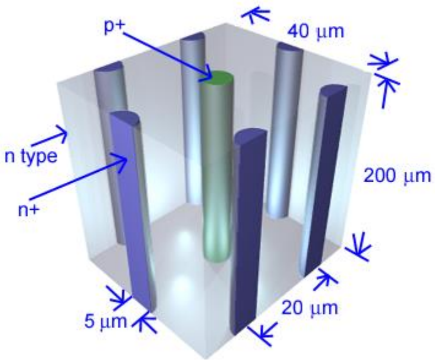


TODAY: Monolithic
25 – 50 μm



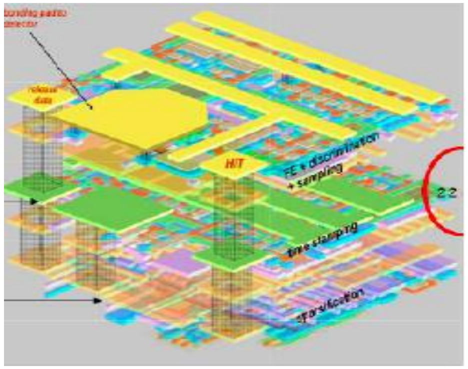
Integrated sensor & electronics: Less X0, no bonding, low noise

TODAY: 3D
Detectors (25–50 μm)



Lower V_{dep} (power)
Faster charge collection

Day After Tomorrow:
3D TSV (< 20 μm)



3D vertical Integration (TSV)

Motivation to develop new Pixel Detectors:

- Decrease fabrication cost
- Develop thinner pixel systems
- Easy fabrication of large area devices
- Integrate More (= denser) Intelligence

Trends and Perspectives:

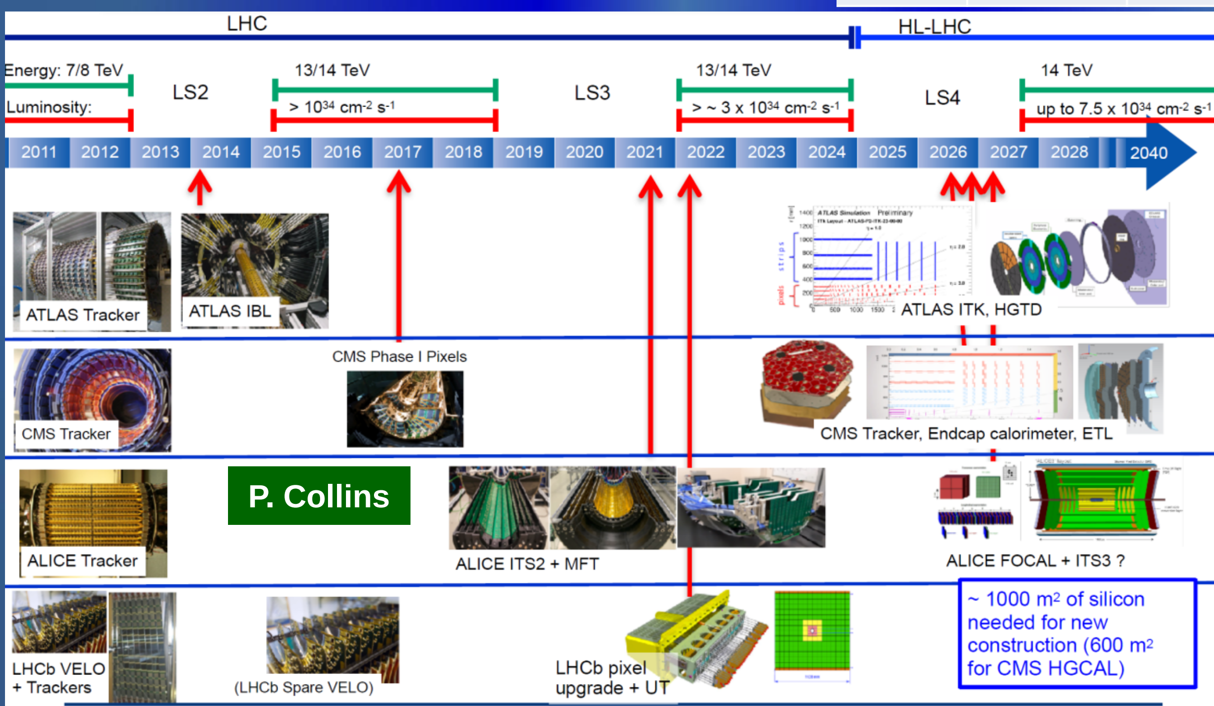
- Improve rad. hardness (p-type bulk)
- Reduce the thickness to 50 mm
- From 6” to 8” and 12” wafers
- R&D on SLID/TSV interconnect.

Silicon @ LHC: State-of-the-Art & Upgrades

Lots of common developments for ATLAS, CMS Pixel Upgrades @ HL-LHC (2026):

- ✓ Pixel chips based on common 65 nm CMOS RD53 development
- ✓ Planar n-in-p sensors → cost-effective single sided processing
- ✓ 3D sensors for innermost layers;
- ✓ Option of MAPS for outer pixel layer (ATLAS)
- ✓ CO2 cooling, Serial powering , LpGBT

Exp. / Timescale	Application Domain	Tech.	Detector size / Module size / Channel count	Radiation Environment	Special Req. / Remarks
ATLAS ITK Upgrade CERN LS3	Hadron Collider (Vertex / Tracking)	Si hybrid pixels (n-in-p), 3D innermost, Si-Strips	**Total area:** pixel – 12.7 m² ; strips - 165 m² **Single unit:** pixel- 50x50 (25x100) μm² strip len./pitch: ~24 – 80 mm / ~70 μm **Channels count :** pixels – 5 G ; strips – 60 M	**Fluences up to 2 x 10^{16} n_{eq}/cm²**	Option for outermost pixel layer: MAPS RD53 ASIC 65 nm CMOS
CMS Tracker Upgrade CERN LS3	Hadron Collider (Vertex / Tracking)	Si hybrid pixels (n-in-p), 3D innermost, Si-Strips	**Total area:** pixel - 4.9 m² ; strips - 200 m² **Single unit:** pixel- 25x100 (50x50) μm² strip len./pitch: 50-24-1.5 mm /~100 μm **Channels count :** pixels – 3 G ; strips – 175 M	**Fluences up to 2.3 x 10^{16} n_{eq}/cm²**	Special p_T-modules in outer strip layers RD53 ASIC 65 nm CMOS
ALICE ITS Upgrade CERN LS2	Heavy Ion Physics (Tracking)	CMOS MAPS, 7 barrel layers	**Total area:** 10 m² ; **Single unit:** pixel size 30x30 μm² **Channels count :** 12.5 G	**Fluences up to 1.7 x 10^{13} n_{eq}/cm²**	0.3% X_0 per layer (inner barrel) ASIC: 180 nm TowerJazz
LHCb VELO Upgrade CERN LS2	Hadron Collider (B Physics)	Si hybrid pixels (n-in-p)	**Total area:** 0.12 m² ; **Single unit:** pixel size 55x55 μm² **Channels count :** 41 M	**Fluences up to 8 x 10^{15} n_{eq}/cm²**	130 nm CMOS, 40 MHz VELOPIX readout, rates up to 20 Gb/s
LHCb Upstream Tracker Upg. CERN LS2	Hadron Collider (B Physics)	Si strips (n-in-p & p-in-n)	**Total area:** 9 m² ; **Single unit:** strip length/pitch: 50 -100 mm / 100 – 200 μm² **Channels count :** ~ 500k	**Fluences up to 5 x 10^{14} n_{eq}/cm²**	
BELLE II PXD / SVD	e+e- Collider (B Physics)	DEPFET / Si-strips (p-in-n)	**Total area:** 0;03 m² / 1.2 m² ; **PXD unit:** pixel size ~50x50 μm² **SVD unit: strip-** 120 mm / 50–240 μm² **Channels count :** 7.7 M / 245 k	**Fluences up to 10^{13} n_{eq}/cm²**	0.15 X_0 per layer



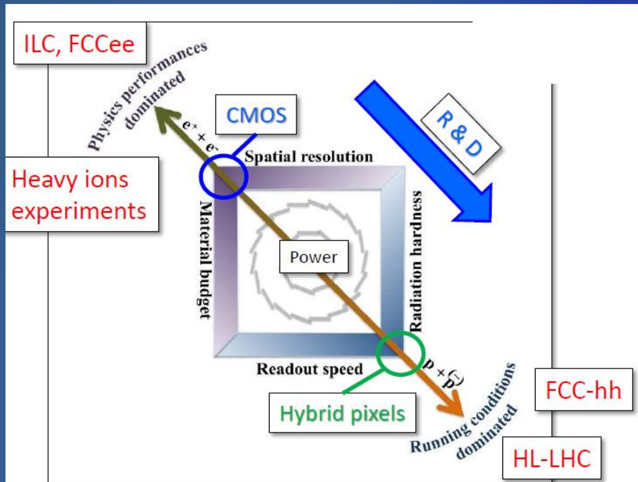
Pixel Systems will enlarge dramatically:

- Surface: ATLAS by factor of ~15
- Channel count : ALICE will reach 12.5 billion pixels with CMOS MAPS
- Cell size: LHCb by ~1000 (strips → pixels)

✓ The Si-strip sensors will consist of (n-in-p) and replace (p-in-n) → radiation hardness consideration,

✓ 3D sensors develop. (FBK, CNM) has been focused on ATLAS-IBL pixels plus several joint MPW production runs with CMS / LHCb.

Vertex and Tracking Systems: State-of-the-Art



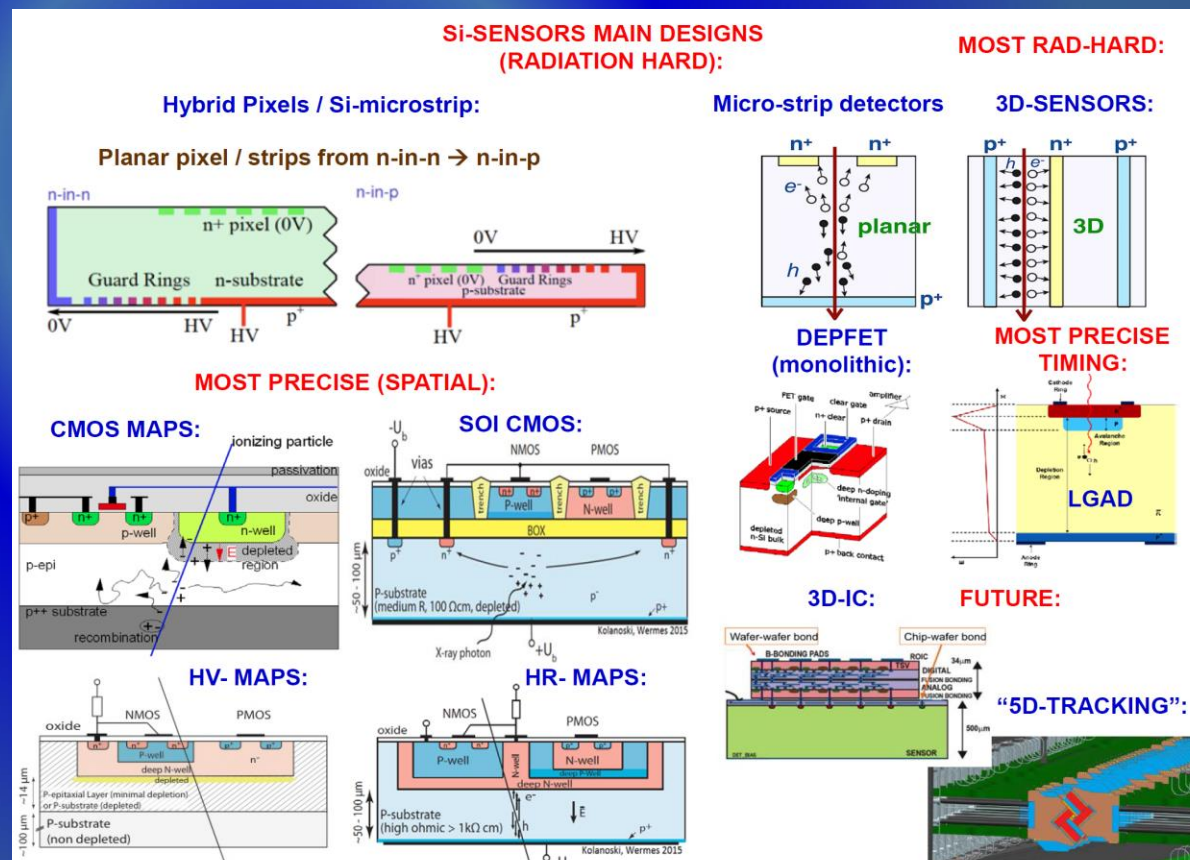
- ✓ Basic applications are optimized for two different realms of interest : electron and hadron colliders → different optimizations/requirements (pp: radiation hardness, speed; e+e-: granularity, material budget)
- ✓ Design problems include: granularity vs the power (particularly for precision timing) and the inactive material to service power and data readout etc. for both accelerator types. Radiation hardness and a strong emphasis on data reduction / feature extraction for the on-detector electronics are particular issues for hadron colliders.

Hadron Colliders:

- ✓ Hybrid pixel detectors (planar & 3D)
- ✓ HV/HR-CMOS for outer pixel layers for HL-LHC upgrades;
- ✓ LGADs for ps-timing

Lepton Colliders:

- ✓ CMOS (STAR HFT, ALICE ITS)
- ✓ DEPFET (Belle II)
- ✓ Chronopix
- ✓ SoI
- ✓ FPCCD
- ✓ 3D-IC (Global Foundries, LAPIX, TJas,…industries)



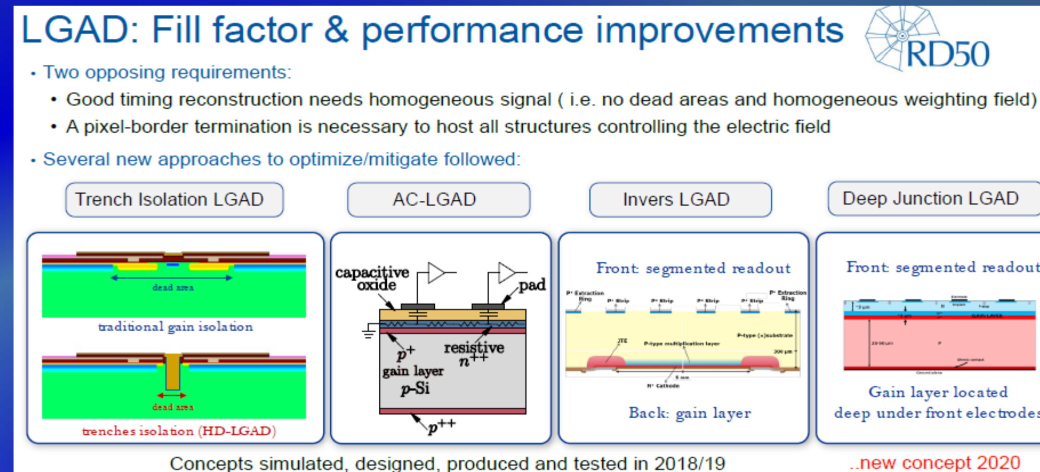
RD50 Collaboration: Radiation Hard Semiconductor Devices

Sensors for 4D Tracking: Development of Radiation Hard Timing Detectors (LGAD)

Incredible success story → pioneered by RD50 and CNM since 2010 (> 50 production runs)

Areas of LGAD developments within RD50:

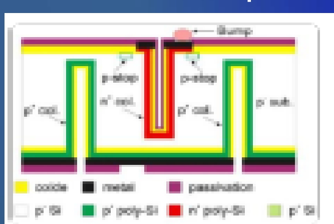
- Timing performance
  (~ 25 ps for 50 um sensors)
- Fill factor and signal homogeneity
- Radiation Hardness (~$2x10^{15}$ n_{eq}/cm^2)
- Performance Parameterisation Model

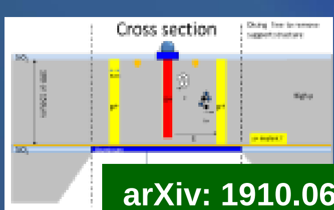


One of the biggest riddles remains the understanding of the radiation damage microscopic mechanisms that lead to the degradation of the gain layer in the LGAD devices.

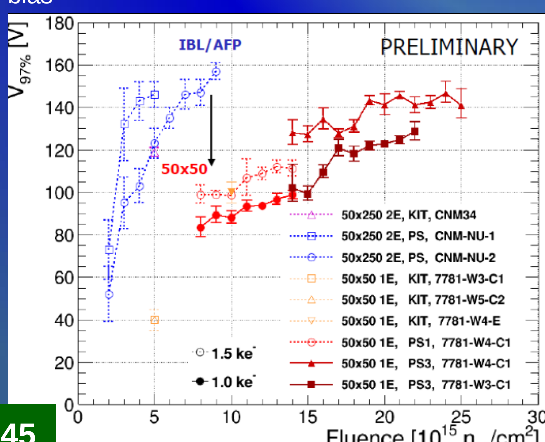
Optimization of 3D sensors for HL-LHC Upgrades:

Good efficiency even up to ~ $3x10^{16}$ n_{eq}/cm^2 & time resolution: 30 ps at V_{bias} > 100V and T = -20C

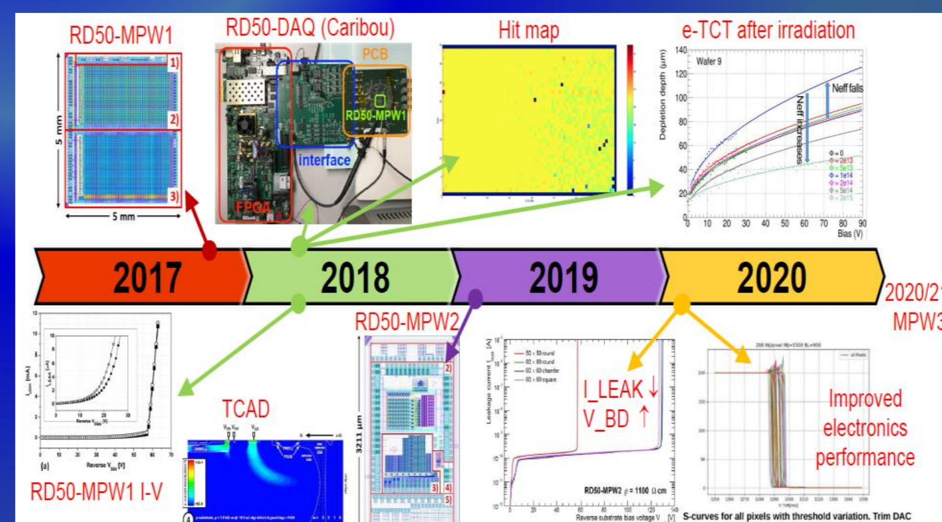


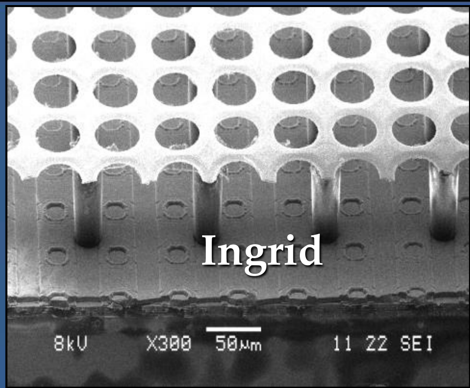


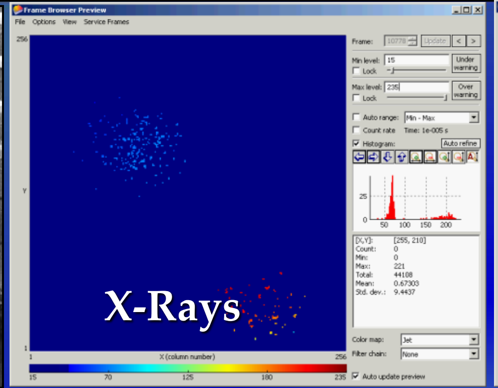
arXiv: 1910.06045

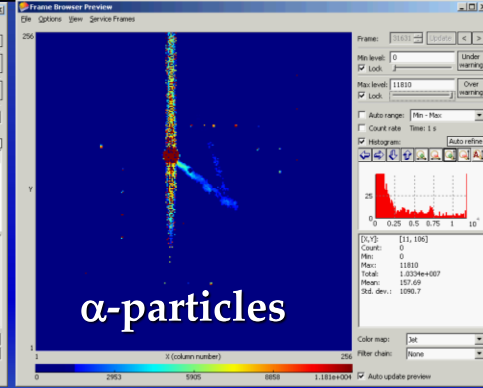


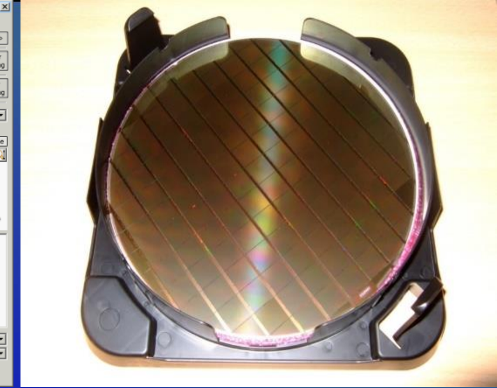
Development of Radiation-Hard (HV-CMOS) sensors:

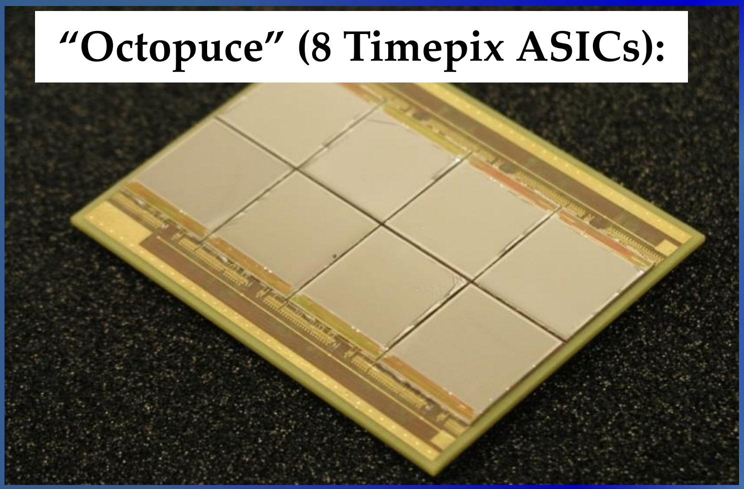






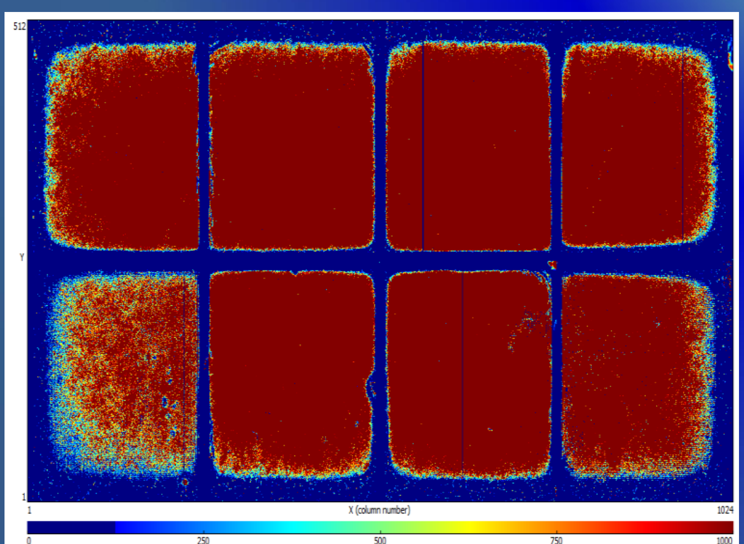


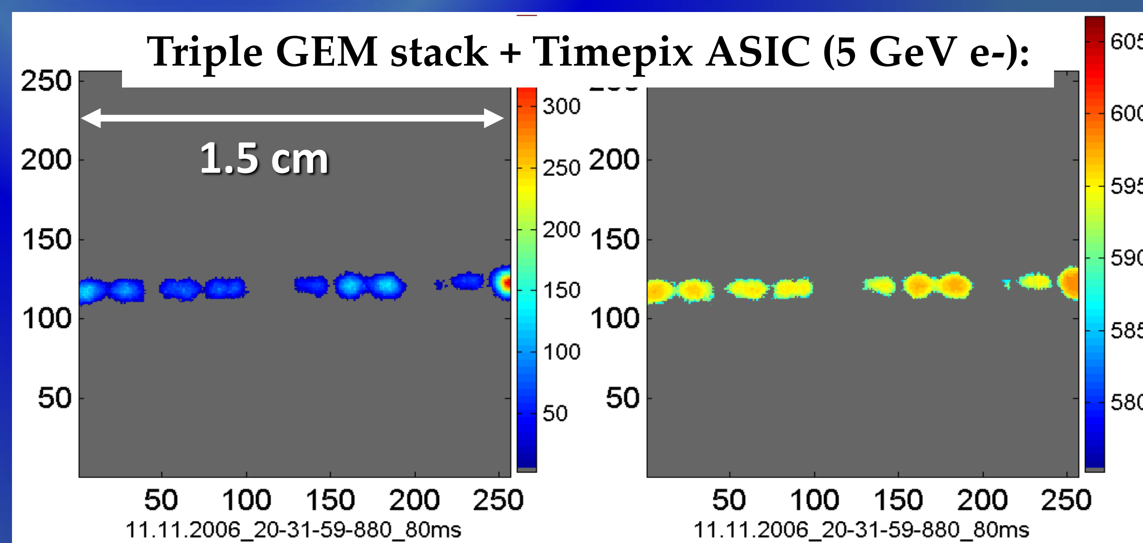




ULTIMATE « MARRIAGE » OF GASEOUS and SIICON DETECTORS –

PIXEL READOUT of MICRO-PATTERN GASEOUS DETECTORS

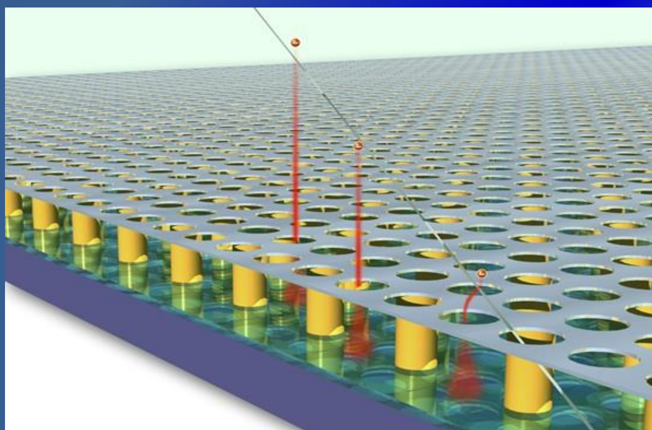


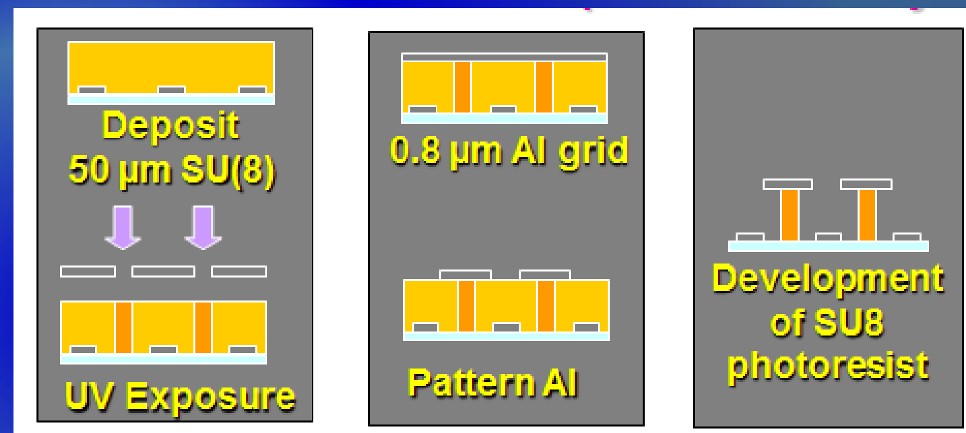


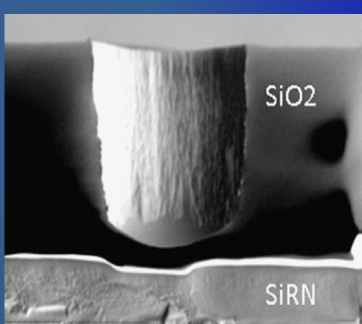
Pixel Readout of MPGDs: “GridPix” Concept

“InGrid” Concept:* *By means of advanced wafer processing-technology* *INTEGRATE MICROMEGAS* *amplification grid directly* *on top of CMOS (“Timepix”) ASIC

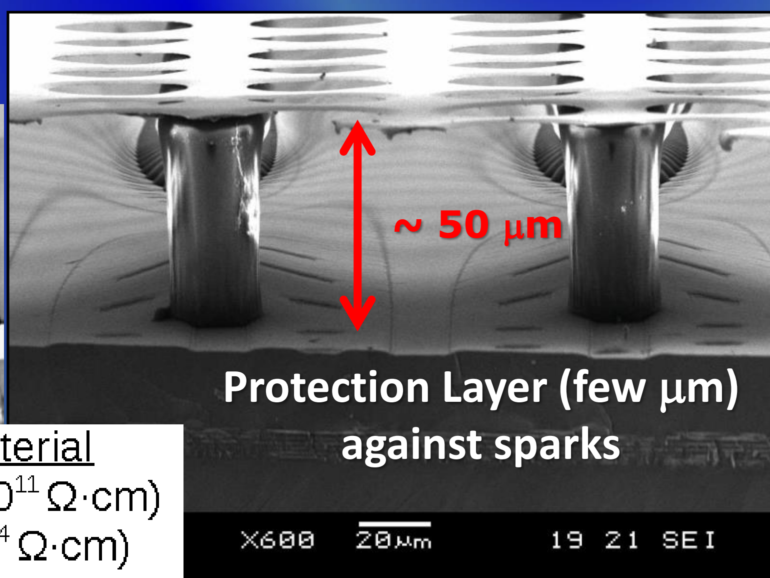
3D Gaseous Pixel Detector → 2D (pixel dimensions) x 1D (drift time)

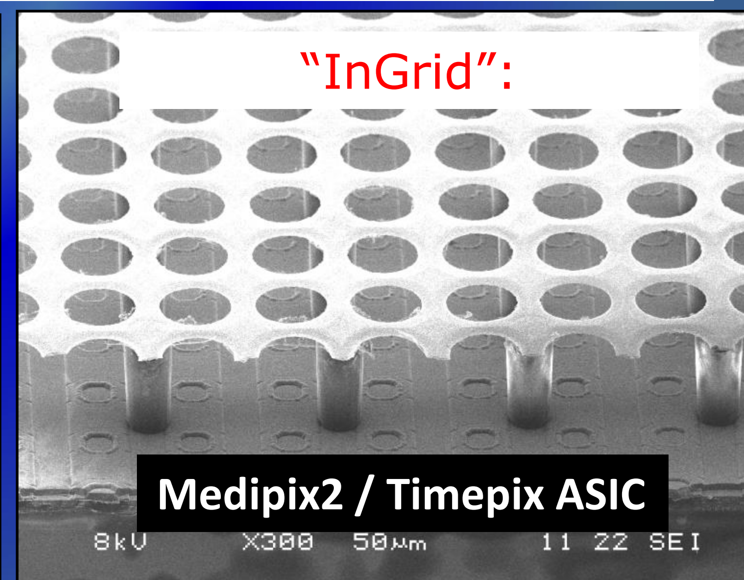


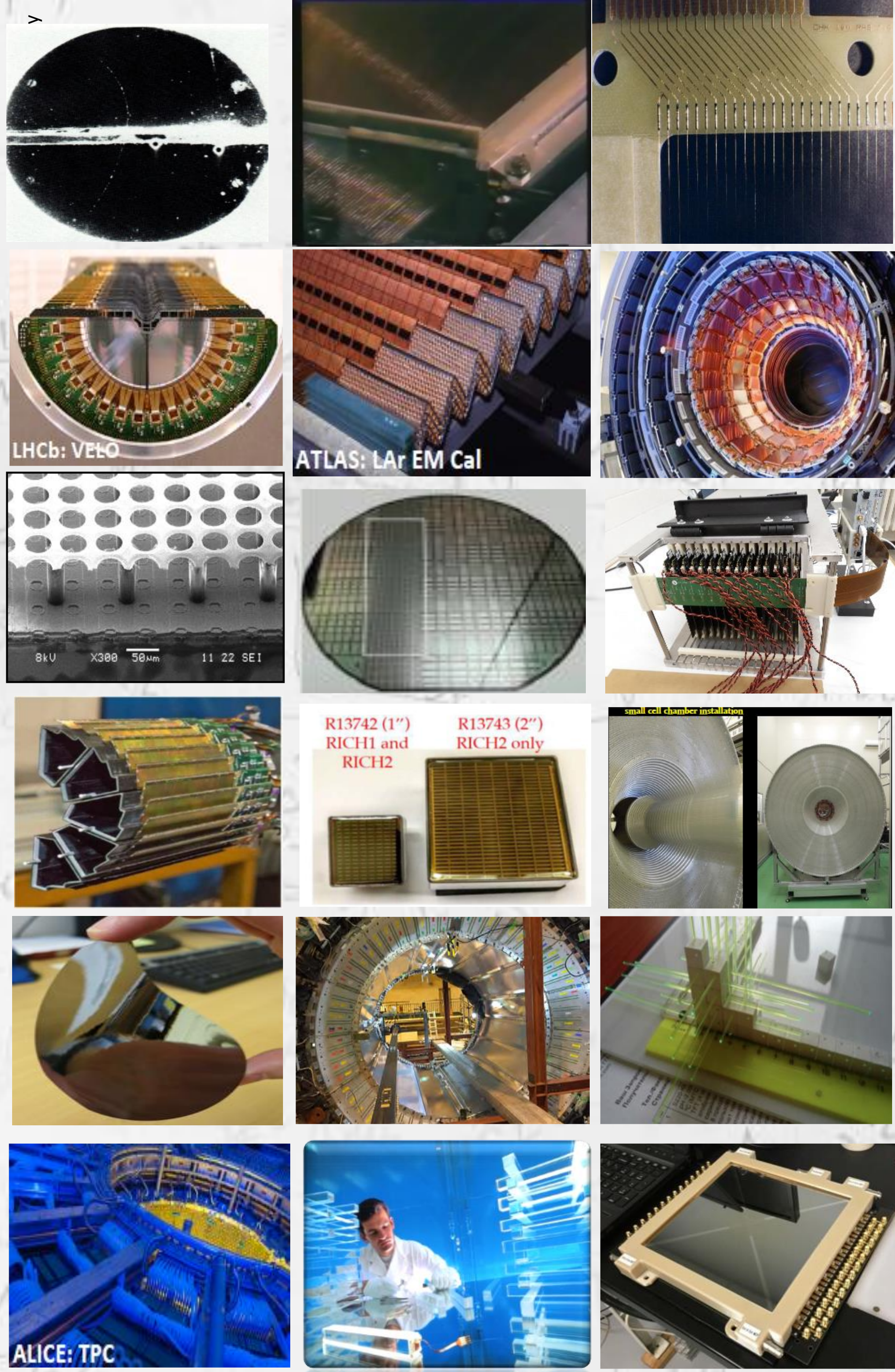




high resistive material
15 µm aSi:H (~10^{11} Ω·cm)
8 µm Si_XN_Y (~10^{14} Ω·cm)







- **Particle Interactions with Matter**
- **"Classic" Detectors (historical touch...)**
- **Advancing Concepts Tracking Detectors: Gaseous Detectors**
- **Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors**
- **Advancing Concepts in Picosecond-Timing Detectors**
- **Advanced Concepts in Particle Identification (PID) & Photon Detectors**
- **Advanced Concepts in Calorimetry**
- **Advanced Concepts in TDAQ, Computing**

Advanced Concepts in PARTICLE IDENTIFICATION (PID)

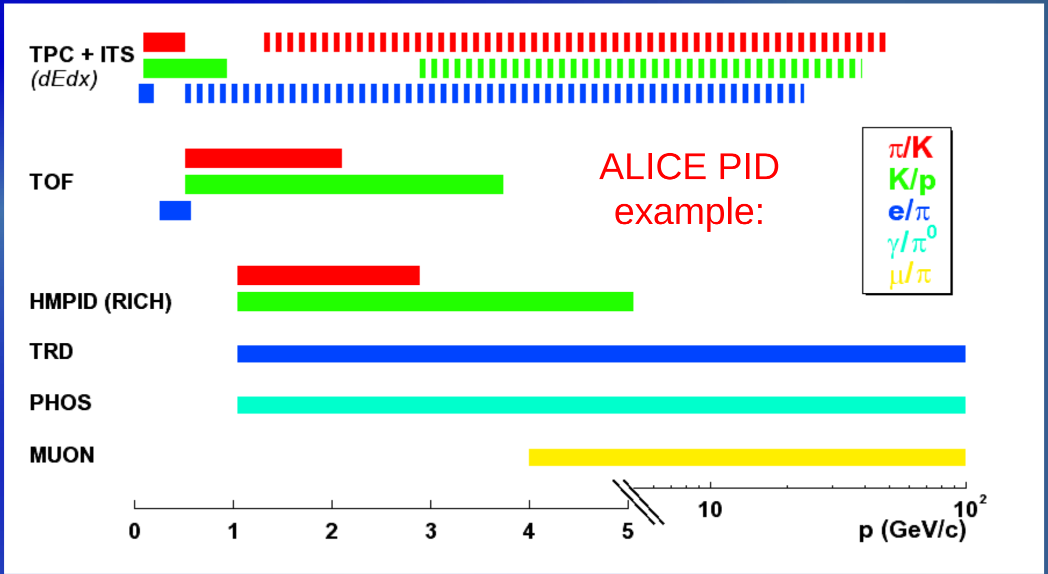
Essential to identify decays when heavy flavour are present: everywhere

Three legs: dE/dx, Time-of-Flight, Cherenkov radiation

Admirable workmanship in radiators and light transport:

- ✓ **Vacuum Photon Detectors**
  - – PMT, MaPMT, MCP - PMT
  - – Hybrid Tubes (APD, HAPD)
  - - LAPPD
- ✓ **Solid State Photon Detectors**
  - – Silicon-based (VLPC, CCD, SiPM)
- ✓ **Gas-based Photon Detectors**
  - - Photosensitive (TMAE/TEA in gas)
  - - MWPC / MPGD + CsI
- ✓ **Superconducting Photon Detectors**
  - – Transition Edge Detectors
  - – Kinetic Inductance detectors
  - - Quantum dots, carbon nanotubes

Excellent PID capabilities by combining different techniques over a large momentum range



- ➢ Threshold Cherenkov Counters – photon counting (Aerogel + PMT)
- ➢ RICH Detectors (particle momentum and velocity → Cherenkov angle and/or yield):
  - - TOP principle: 1-time of propagation + Cherenkov angle (instead of 2D imaging)
  - - RICH + TOF: Measure timing of Cherenkov light
  - - ALICE MRPC: Gaseous timing
  - - TRD: Cluster Counting method (dN/dx)

Imaging Cherenkov Detectors

$$\cos\theta = \frac{1}{\beta n}$$

$$m = \frac{p}{\beta\gamma}$$

$$m = \frac{p}{\beta\gamma} = p\sqrt{n^2\cos^2\theta_c - 1}$$

$$\frac{\Delta m}{m} = \sqrt{\left(\frac{\Delta p}{p}\right)^2 + \left(\gamma^2 \cdot tg\theta \cdot \Delta\theta\right)^2}$$

$$\sigma_\theta^2 = \sum_i \Delta\theta_i^{\,2} \Rightarrow \sigma_{\theta_c} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

- ➔ minimize S_q
- ➔ maximize $N_{p.e.}$

➔ **low chromaticity**, **high granularity**, **high packing density**

➔ **Goal**: detect the maximum **number of photons** with the best **angular resolution**

Separation power:

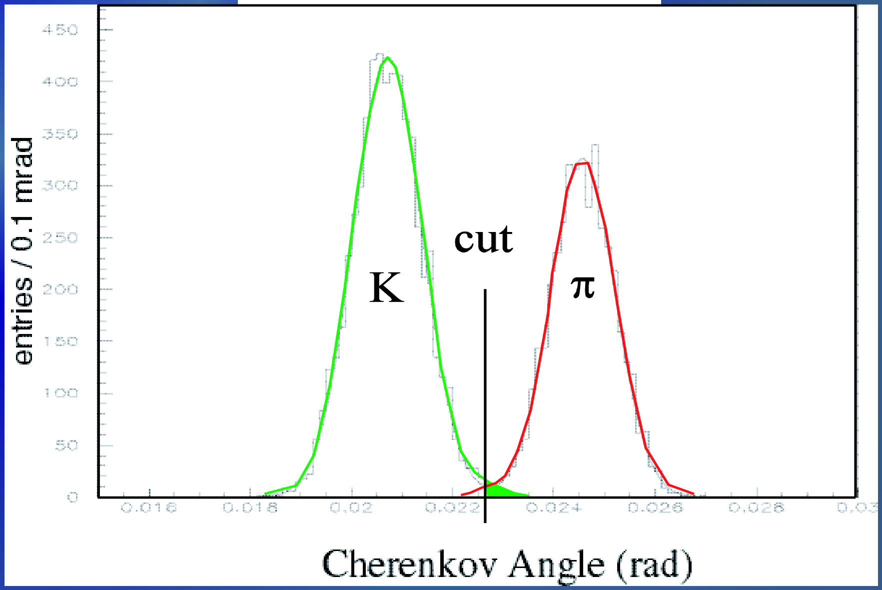
$$\theta_2 - \theta_1 = n\sigma_{\theta_c}$$

- Separating two particle types using the signal from a RICH detector is illustrated for K and π from a test beam

~ Gaussian response, $\sigma_\theta \sim 0.7$ mrad
Peaks are separated by 4 mrad = 6 σ_θ

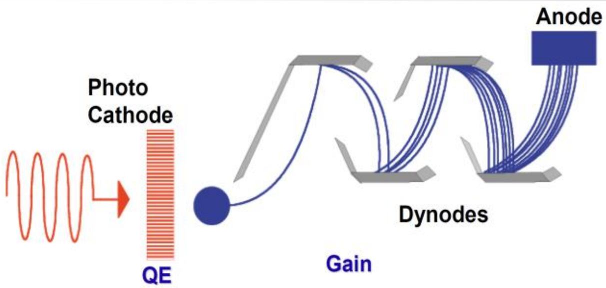
Generally: $N_\sigma = \dfrac{|m_1^2 - m_2^2|}{2\, p^2\, \sigma_\theta \sqrt{n^2-1}}$

- Adjusting the position of the cut placed between the two peaks to identify a ring as belonging to a K or p gives a trade-off between *efficiency* and *misidentification*

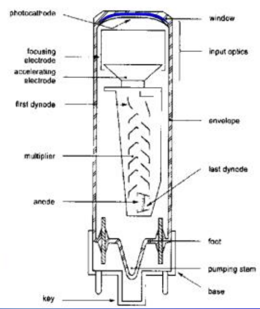


Several Key Photon Detector Technologies

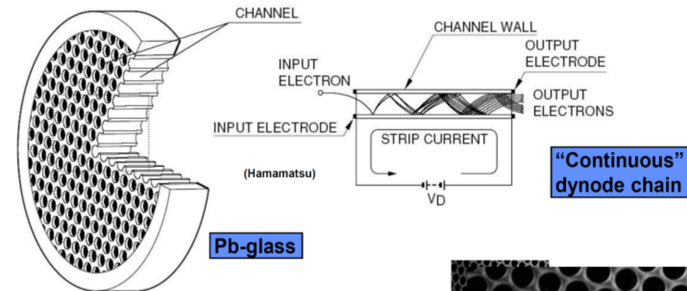
Vacuum photon detectors: Photo Multiplier Tube



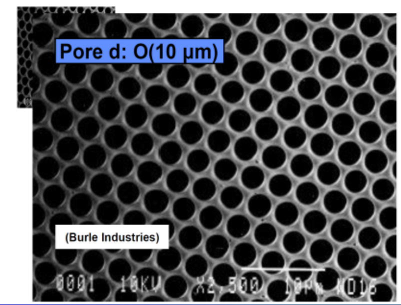
- ❑ Photon-to-Electron Converting Photo-Cathode
- ❑ Dynodes with secondary electron emission
- ❑ Typical gain ~10^6. Transient time spread ~200 ps
- ❑ Sensitive to magnetic field
- ❑ Choice of Photo-Cathode: high QE *for the wavelength of incoming light*
- ❑ Concerns: dynamic range, time dependence of response, rate capability



Vacuum photon detectors: Micro Channel Plate



- ❑ **Gain fluctuations** can be minimized by operating in the saturation mode
- ❑ Kind of **2D PMT**:
  - + high gain up to 5 x 10^4;
  - + fast signal (transit time spread ~20 ps);
  - + less sensitive to B-field (0.1 T);
  - - limited lifetime (0.5 C/cm^2);
  - - limited rate capability (mA/cm^2)

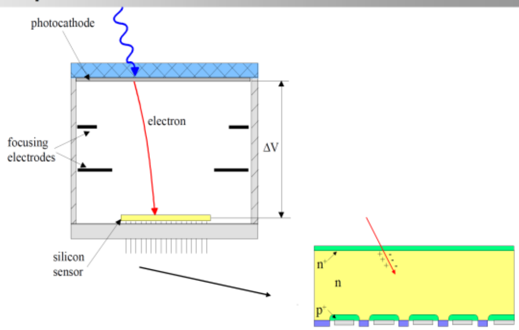


Vacuum photon detectors: HPD

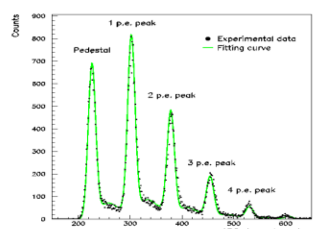
Photo Multiplier Tube
- dynodes and anode
+ silicon sensor

Hybrid Photo Detector

LHCb



- ❑ It takes 3.6 eV to create an electron-hole pair in silicon. Using an accelerating voltage 20 kV → **~ 5000 electron-hole pairs, amplification in 1 step** → Good energy resolution
- ❑ But : High voltage, ion feedback → requires good vacuum



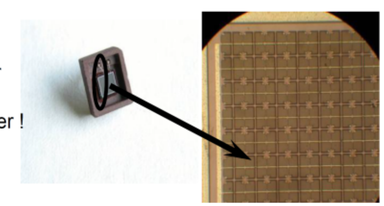
Solid-state photon detectors

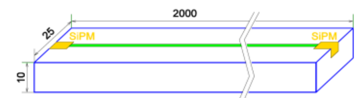
- ❑ **More compact, lightweight, tolerant to MF, cheaper, allow fine pixelization, ...**

E.g.: **Silicium Photon Multiplier (SiPM)**

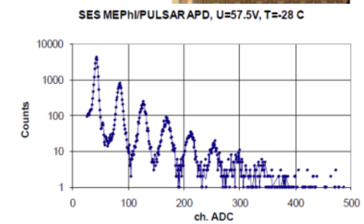
- ❑ Fully solid state photon detector, large array of tiny avalanche photodiods
- ❑ p-n junction under large reverse-bias voltage, packed over a small area and operated in a limited Geiger mode above breakdown voltage ➔ detectable electrical response from low-intensity optical signals, down to single photons
- ❑ Binary output, linearity achieved by summing cell outputs

SiPM 3x3 mm² attached directly to BICRON-418 scintillator 3x3x40 mm³
Signal is readout directly from SiPM w/o preamp and shaper !





- ❑ Sensitive area: 3x3 mm2 # of pixels: 5625
- ❑ Pixel size: 30 μm x 30 μm
- ❑ Depletion region: ~1 μm
- ❑ SiPM noise (FWHM): room temperature 5-8 electrons; -50 C 0.4 electrons



Photon Detection for PID: State-of-the-Art

- RICHes with focalisation
  (SELEX, OMEGA, DELPHI, SLD-CRID, HeraB, HERMES, COMPASS, LHCB, NA62, EIC dRICH)

✓ Extended radiator (gas)
✓ Mandatory for high momenta

- RICHes with Proximity focusing
  (STAR, ALICE HMPID, HERMES, CLEO III, CLAS12, EIC mRICH, Belle ARICH, FARICH (Panda, ALICE, Super Charm-Tau)

✓ Thin radiator (liquid, solid, aerogel)
✓ Low momenta

- DIRC and its derivatives (Detector of Internally Reflected Cherenkov light)
  Babar DIRC,BELLE II TOP, Panda Barrel/Endcap & EIC (focusing DIRCs), LHCb TORCH, FDIRC GLUEX

✓ Quartz as radiator and light guide
✓ Low momenta

- Time-Of-Flight (TOF) detectors
  (ALICE, BES III)

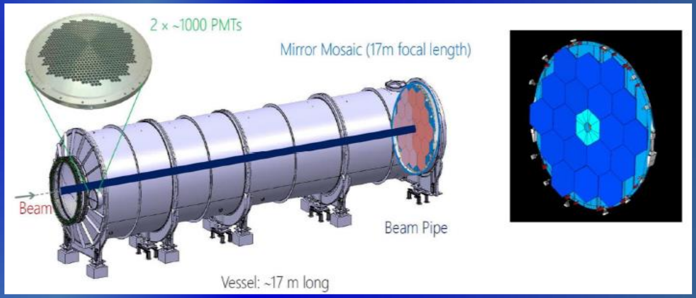
✓ Use prompt Cherenkov light
✓ Fast gas detector

LHCb RICH I and II Upgrade for Run-III:

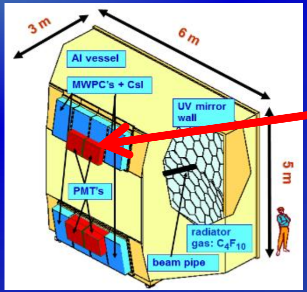
✓ New electronics @ 40 MHz
✓ New optics layout for RICH 1
✓ MaPMTs sill replace HPDs for RICH 1 and RICH2

NA62 RICH with 2000 PMTs :

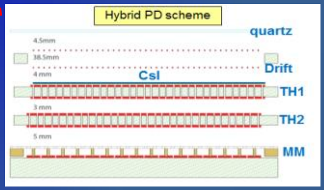
✓ Good test for GPU-based online selection (RICH participates in the low level trigger)



COMPASS RICH Upgrade:



Replace 8 MWPC's/CsI with hybrid (THGEM /Micromgas) with CsI



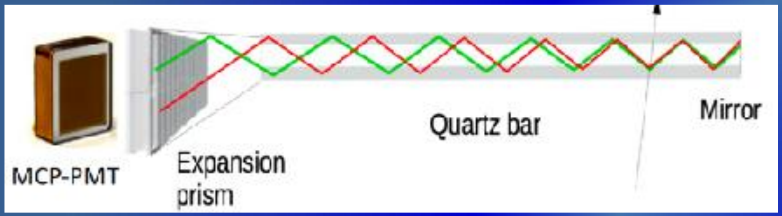
✓ Exploring a possibility to use more robust PC: hydrogenated nano-diamond crystals
✓ R&D towards compact RICH for the future EIC

Many Clever Techniques for Ultra-Fast TOF and TOP

Fast progress in the new DIRC-derived concepts, including time-of-propagation counters - exceptional time-resolution of O(10ps), based on MCP-PMTs

Belle II Time of Propagation RICH (TOP)

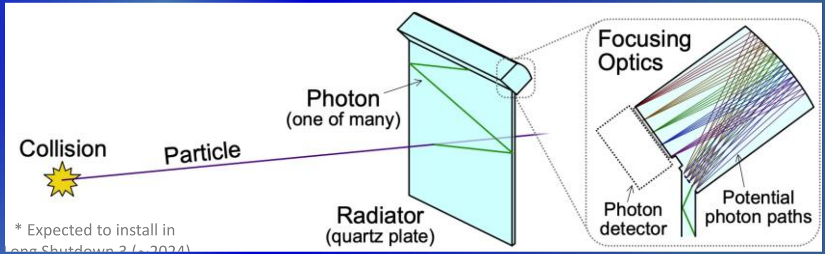
Based on a DIRC concept: instead of 2D-imaging
→ 1D + Time Of Propagation (TOP, path length)



Installed between drift chamber and calorimeter
- ✓ Single photon efficiency; < 100 ps SPTR
- ✓ few mm spatial res.; operation in 1.5T B field

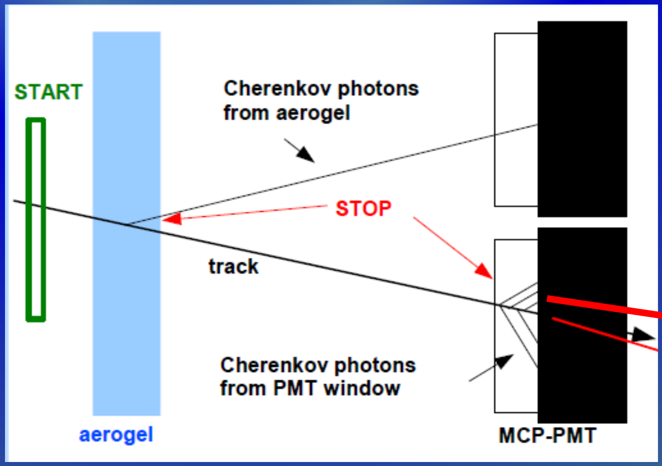
LHCb TORCH (Time Of internally Reflected CHerenkov light) for Run 4/5:

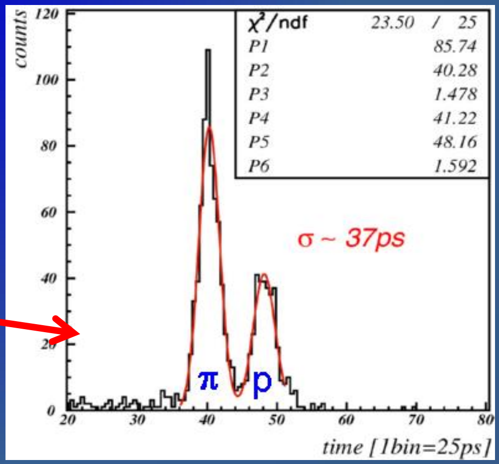
- ✓ Prompt production of cherenkov light in quartz bars
- ✓ Cherenkov photons travel to detector plane via total internal reflection and cylindrical focusing block
- ✓ 70 ps per photon →15 ps per track
- ✓ Photons detected by square micro channel plate PMTs; resolution improved by charge sharing



Generic R&D: combination of proximity focusing RICH + TOF with fastphoto sensors (MCP-PMT or SiPM) using Cherenkov photons from PMT window

Cherenkov photons from PMT window can be used to positively identify particlesbelow threshold in aerogel





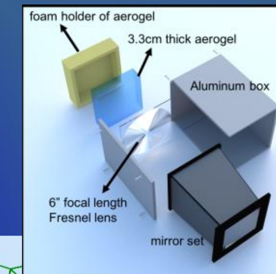
Particle Identification (PID) for Electron-Ion Collider

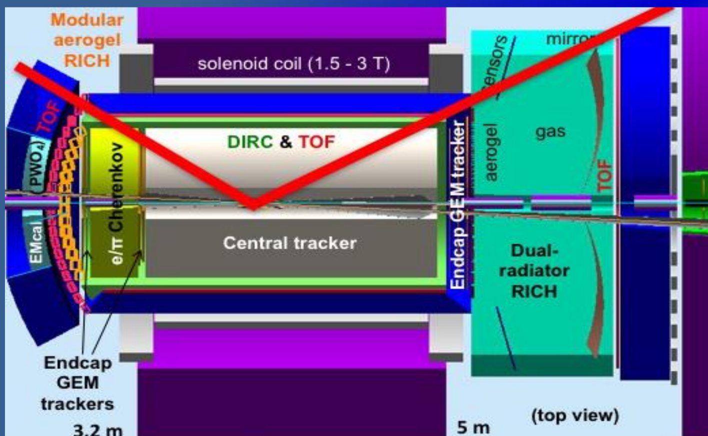
RICH Detectors for Particle Identification @EiC

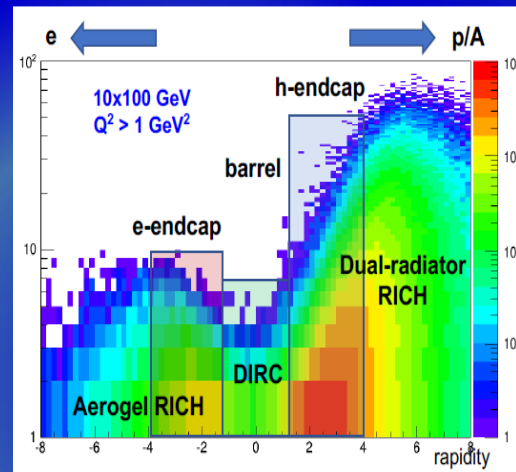
- ✓ **dRICH: dual-radiator (aerogel & C2F6) RICH**
- ✓ **mRICH: lens-focusing modular aerogel RICH**
- ✓ **hpDIRC: compact fast focusing DIRC**

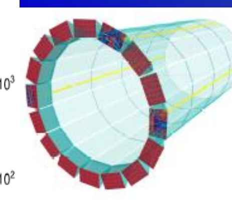
TOF (and/or dE/dx in TPC): can cover lower momenta

mRICH:

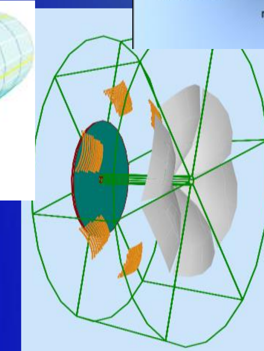








hpDIRC:



dRICH:

General Challenges for Photodetectors:

- ➢ Photodetectors: Big challenge is to provide a realiable highly-pixelated photodetector working at 1.5 – 3 T field
- ➢ SiPMs: high dark count rate and moderate radiation hardness prevented their use in RICH detector, where single photon detector required at low noise
- ✓ MCP-PMTs: very expensive, not tolerant to magnetic fields;
- ✓ Large-Area Picosecond Timing Detector (LAPPD): promising, still not fully applicable for EIR yet → need pixellation, efforts underway, control of cost;

Particle Identification Summary

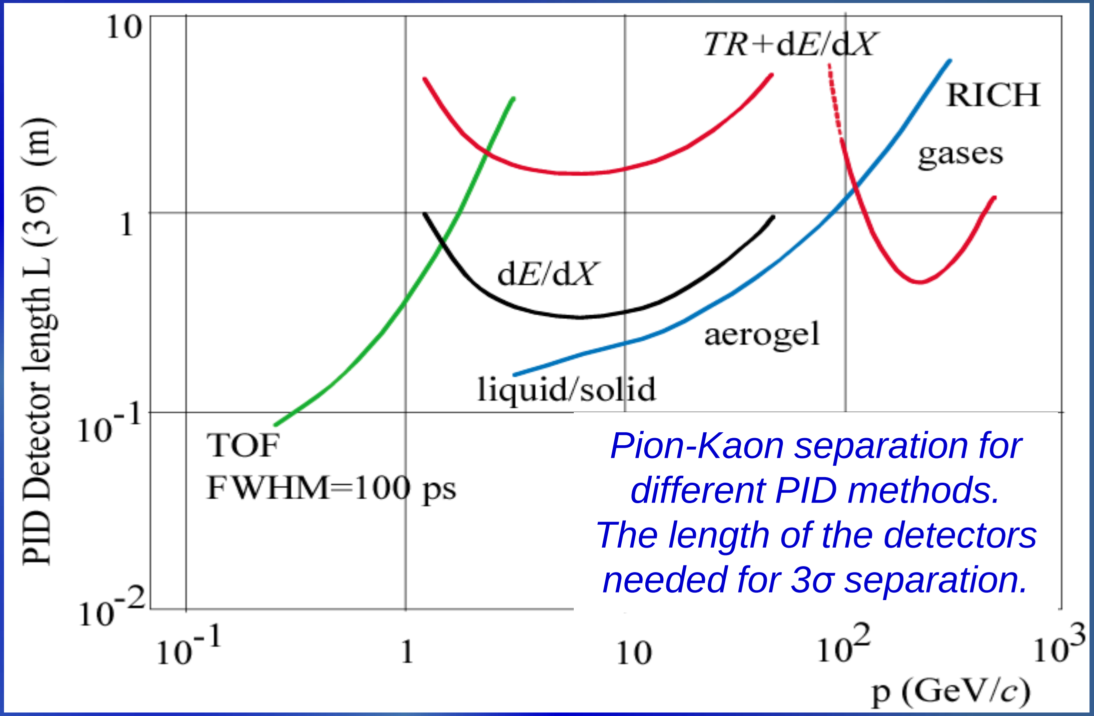
There is a wide variety of techniques for identifying charged particles:

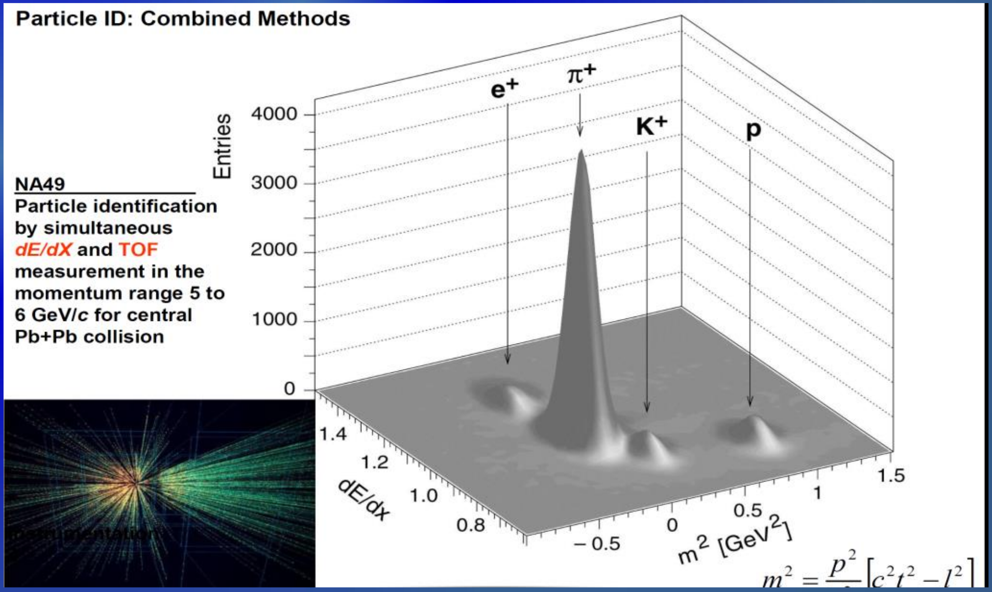
- **Transition radiation** is useful in particular for electron identification

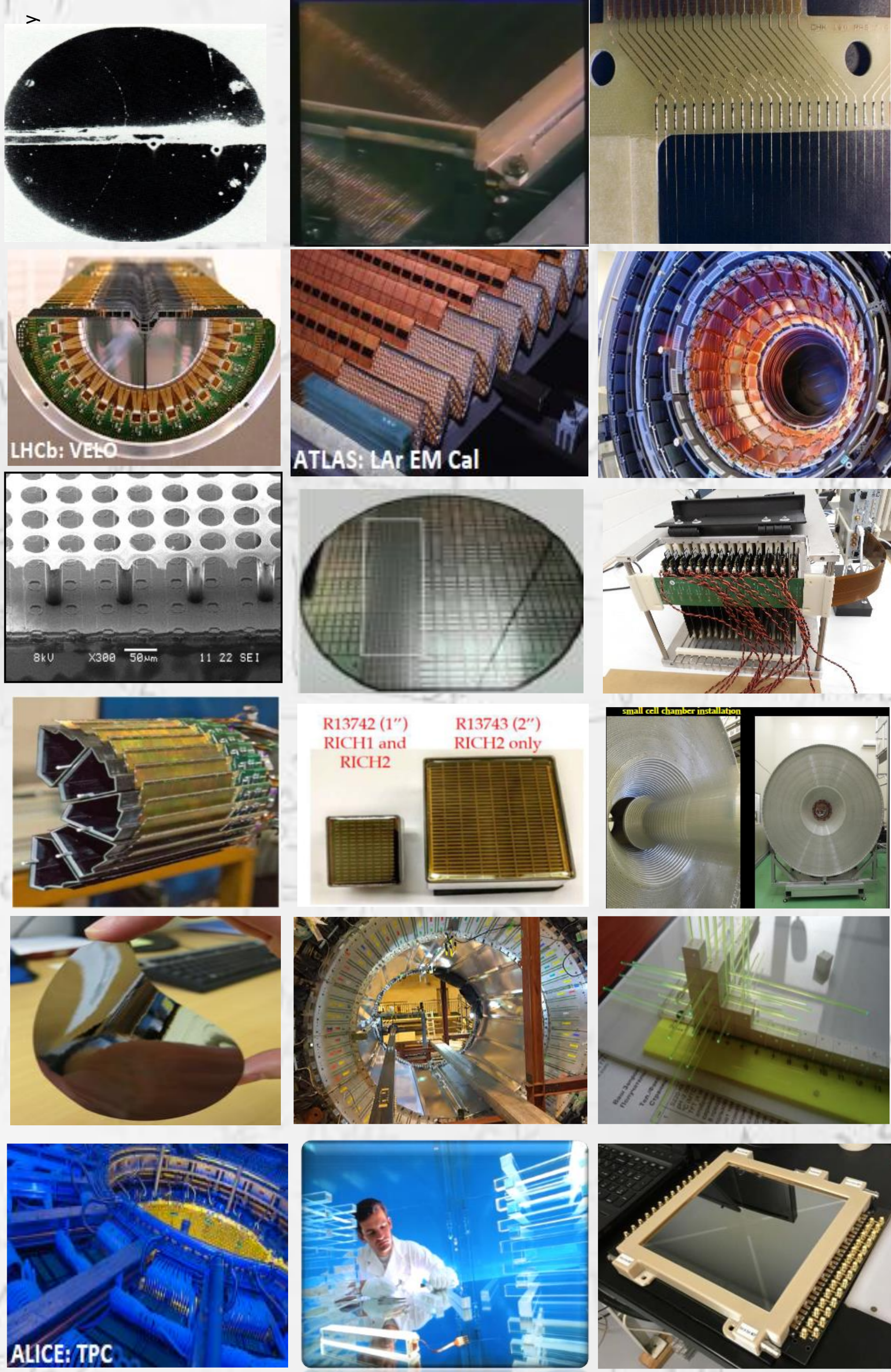
- **Cherenkov** detectors are in widespread use. Very powerful, tuning the choice of radiator

- **Ionization** energy loss is provided by existing tracking detectors but usually gives limited separation, at low *p*

- **Time Of Flight** provides excellent performance at low momentum With the development of faster photon detectors, the range of TOF momentum coverage should increase







- Particle Interactions with Matter
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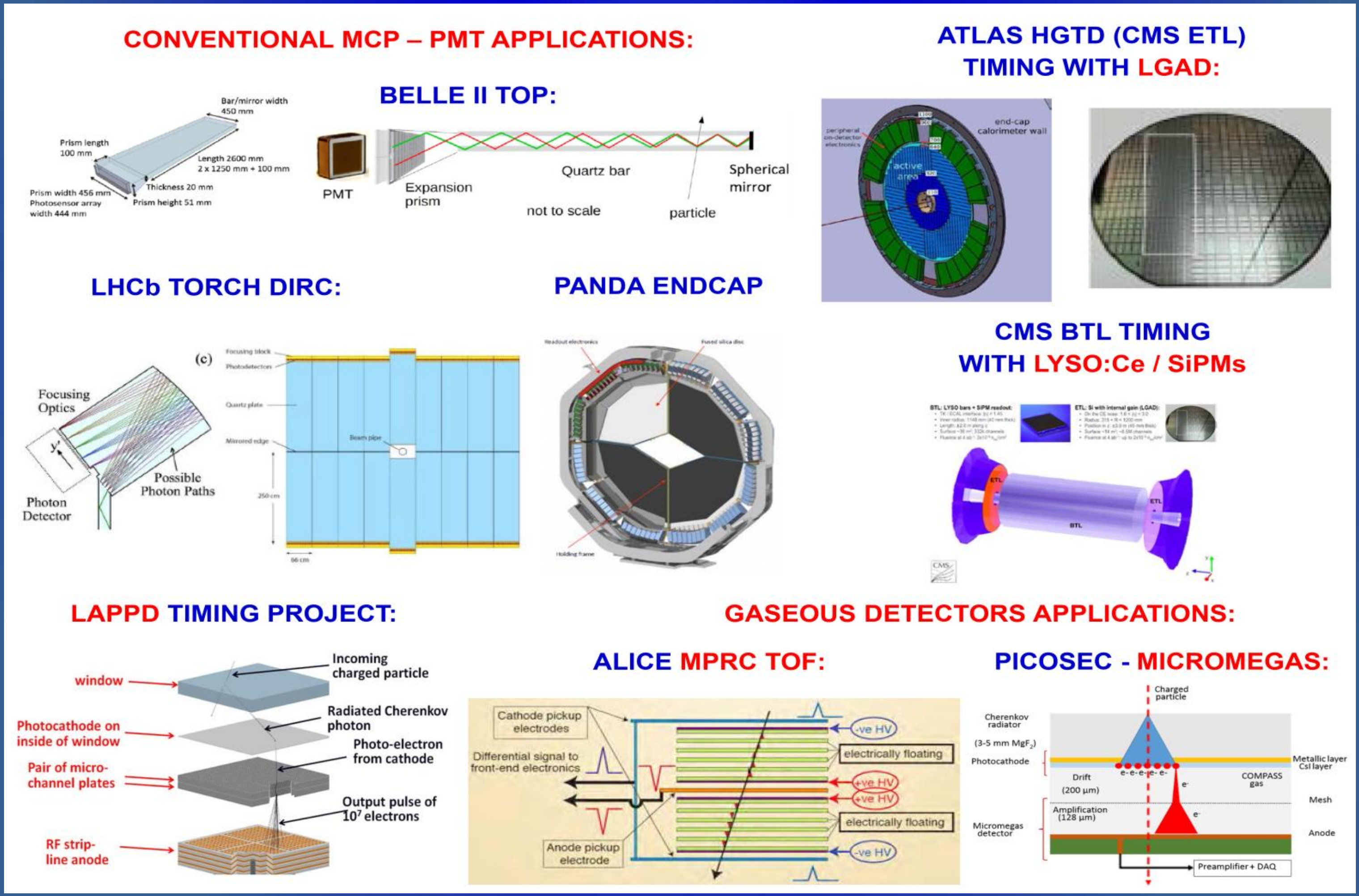
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Advanced Concepts Picosecond (a few 10's) Timing Detectors

Several types of technologies are considered for "Picosecond-Timing Frontier":

- Ionization detectors (silicon detectors or gas-based devices)
- Light-based devices (scintillating crystals coupled to SiPMs, Cherenkov absorbers coupled to photodetectors with amplification, or vacuum devices)



Examples of timing detectors at a level of~ 30 ps for MIPs and ~ 100 ps for single photons

TIMING Detectors with a few 10's of picosecond resolution

Picosecond-level timing was not the part of initial HL-LHC detector requirements:

Became available through pioneering R&D on LGAD / crystals / precise timing with Si:

Fast development of precise timing sensors:

- ✓ 4D pattern recognition for HL-LHC pile-up rejection: tracking ~O(10's) μm & timing detectors ~O(10's) ps
  → ATLAS HGTD, CMS ETL (LGAD)
  → CMS BTL (LYSO +SiPM)
- ✓ ps-timing reconstruction in calorimetry (resolve develop. of hadron showers, triangulate H → γγ prim. vertices)
  → CMS HGCAL (Si & Sci.+ SiPMs)
- ✓ TOF and TOP (RICH DIRC) PID → new DIRC applications (~ 10's of ps & 10's of μm per MIP/pixel)
  → both at hadron / lepton colliders
- ✓ General push for higher luminosity at LHC, Belle-II, Panda, Electron-Ion Collid.
  → Fast timing is needed at colliders, fixed target, and neutrino experiments

- ➢ Regular PMTs → large area, … but slow
- ➢ MCP-PMT → fast, but small, and not available in quantities to over large areas:
  → ultimate time resolution ~ 3.8 ps (single-pixel devices)
  → radiation hardness up to ~ 20 C/cm (HPK, ALD-coated MCP-PMT°

Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm² *** (tracks)	-	~60 ps/track (present)***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm² ** (tracks)	-	Plan: ~20 ps/track	[4]
MCP-PMT	Beam test	-	-	< 10 ps/track *	[7,8,9]
MCP-PMT	Laser test	-	-	~27 ps/photon *	[14]
MCP-PMT	PANDA Barrel test	10 MHz/cm² * (laser)	~20 C/cm² *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm² ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm² *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm² ** (photons)	5 C/cm² **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon***	[23]
Low gain AD	ATLAS test	~40 MHz/cm² ** (tracks)	-	~ 34 ps/track/single sensor *	[34,35]
Medium gain AD	Beam test	-		< 18 ps/track *	[39]
Si PIN diode (no gain)	Beam test (electrons)	-		~23 ps/32 GeV e⁻	[8]
SiPMT (high gain)	Beam test – quartz rad.	-	< 10^{10} neutrons/cm²	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm²	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm² * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm² * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm² * (laser test)	-	~76 ps/photon *	[31,32,40]

* Measured in a test
** Expect in the final experiment
*** Status of the present experiment

J. Va'vra, arXiv: 1906. 11322

Challenges:

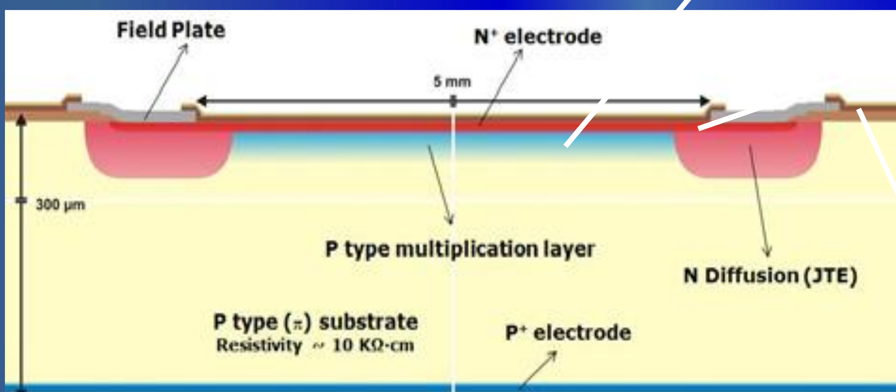
- ✓ Radiation hardness: LGAD-sensors, 3D-trench Si sensors, …
- ✓ Large scale applications : system aspects of timing detectors
- ✓ "5D reconstruction": space-points / ps-timing are available at each point along the track → LHCb EoI for LS4 is of general interest across experiments;
- ✓ LAPPD → large-area ps- PID/TOF for hadron/lepton colliders
  Incom Inc. company started to produce LAPPDs → cost still has to be controlled

Basic Principles: Low-Gain Avalanche Detectors (LGAD)

LGADs exploit the avalanche phenomenon of a reverse-biased p-n junction: ***Internal gain (~10) is optimized for high bias (fast collection, reduced trapping), low noise, high rate***

LGAD Structure:

- Highly resistive *p*-type substrate
- ***n*+ and p+ diffusions** for the electrodes
- ***p* diffusion** under the cathode → enhanced electric field → **multiplication**



Electric field profile is critical since the charge multiplication depends **exponentially** on it.

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

$$\alpha_{e,h}(E) = \alpha^{\infty}_{e,h}\, e^{-\left(\frac{E_o}{E}\right)}$$

Critical regions of the LGAD design:

- **Central area (gain region, multiplication layer)**
  Uniform electric field, sufficiently high to activate mechanism of impact ionization (multiplication)

- **N - Implant Edge Termination**
  - Lightly-doped N-type deep diffusion (JTE) and addition of a field plate
  - Allows high electric field in the central r region since breakdown voltage VBD(Edge) >> VBD (Central)

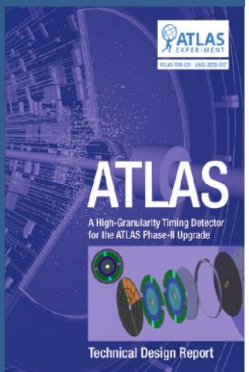
- **Periphery**
  - P-spray/stop: counteracts inversion and cuts off current path
  - Biased guard ring around the detection region collects the surface component of the current

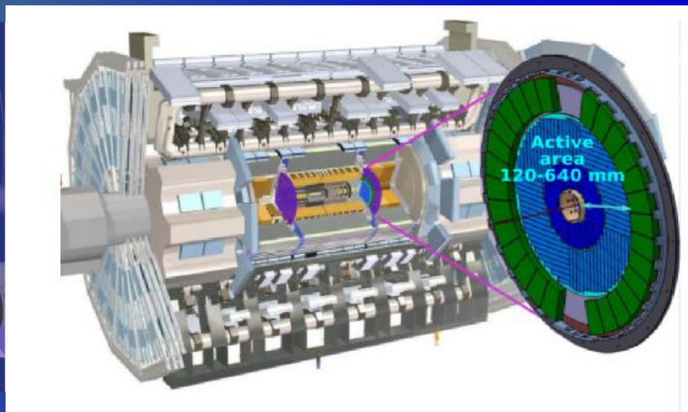
TIMING DETECTORS for ATLAS / CMS Phase-II Upgrade

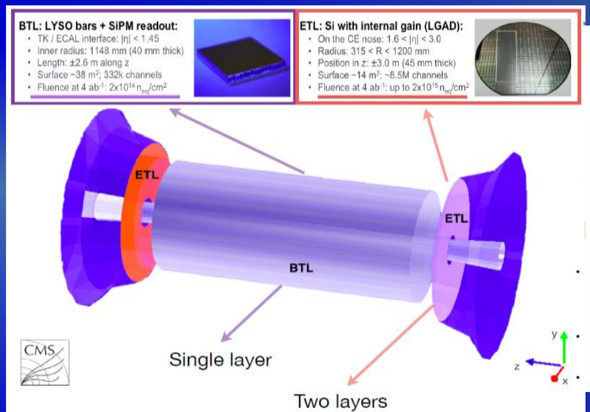
ATLAS High Granularity Timing Detector:

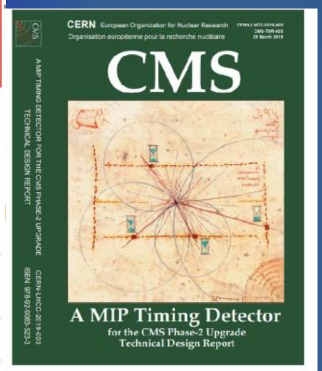
CMS Endcap Timing Detectors:

Equipped with LGADs (1.3 x 1.3 mm^2 pads) targetting > 50 ps resolution (rad-hard only viable solution)





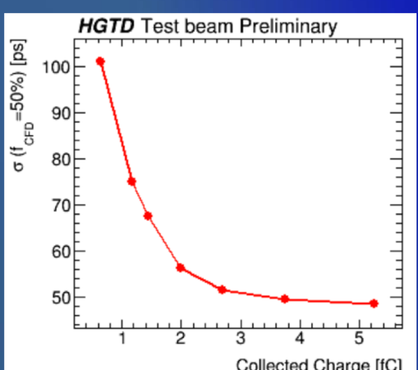


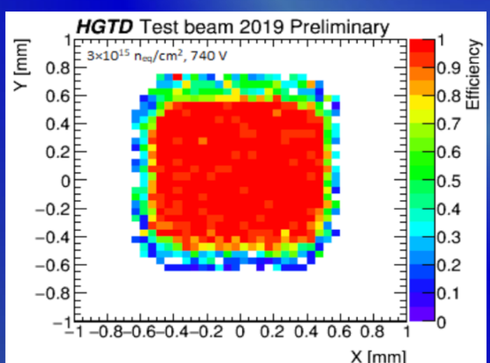


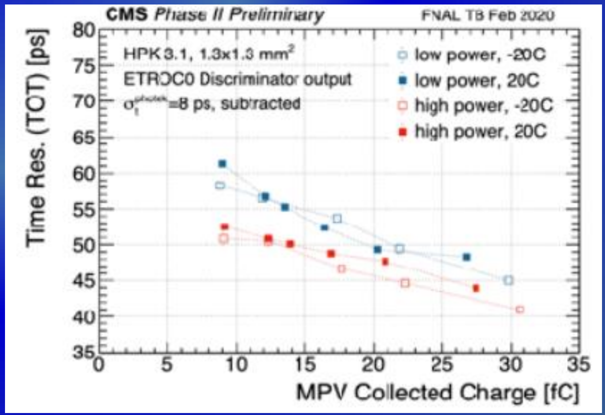
Two double sided layers in front of Calorimeter endcaps:
Fluence < 2.5 x 1015 neq/cm2
Coverage: 2.4 < η < 4.0 with 12 cm < R < 64 cm @ z = 3.5 m

Two double sided layers in front of Calorimeter endcaps:
fluence < 1.7 x 1015 neq/cm2
Coverage: 1.6 < η < 3.0 with 0.31 < R < 1.2 @ z = 3 m

Post irradiation: 4 fC and 50 ps achieved (high/uniform efficiency)







P. Collins @ ICHEP2020

Pre irradiation 40-50 ps after discriminator with full efficiency

- ➢ LGAD are currently produced by 3 foundries (CNM, FBK, HPK)
- ➢ LHCb is developing a time-tracking device O(100 ps) device, based on 3D trench Si-sensors with a more uniform field/charge collection, and a goal to withstand fluence of 10^{16} - 10^{17} n_{eq}/cm2

Towards Large Area in Fast Timing GASEOUS DETECTORS

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m^2) achieved time res. ~ 60 ps
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 µm-thick glass → down to 20 ps time resolution

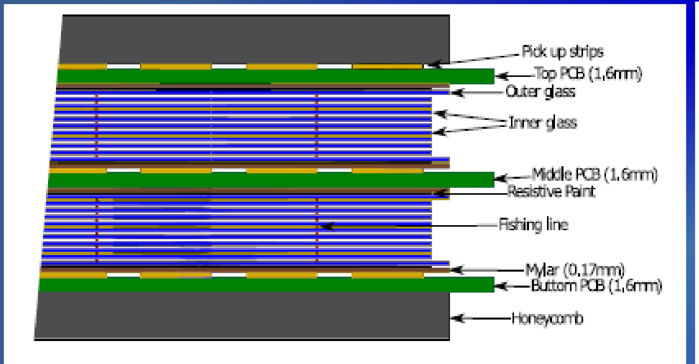
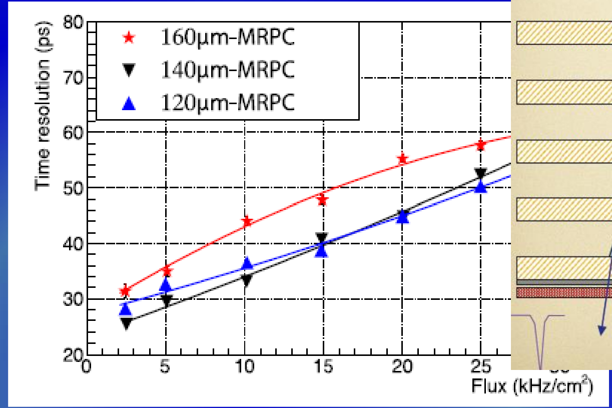
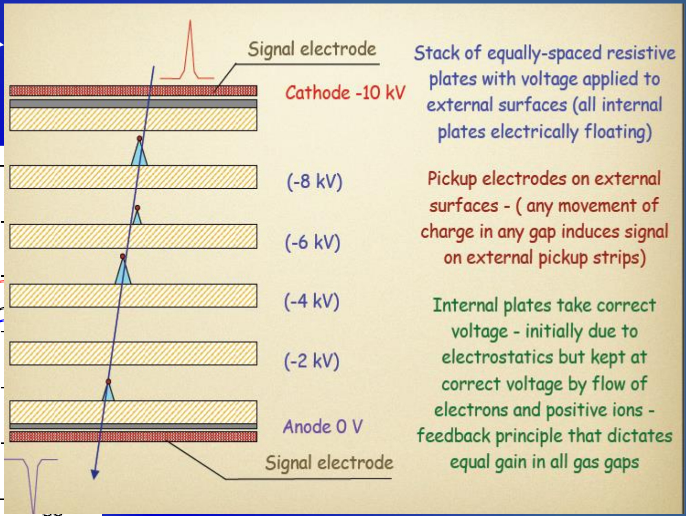


Fig. 1. Cross section of the double stack 20-gap MRPC.

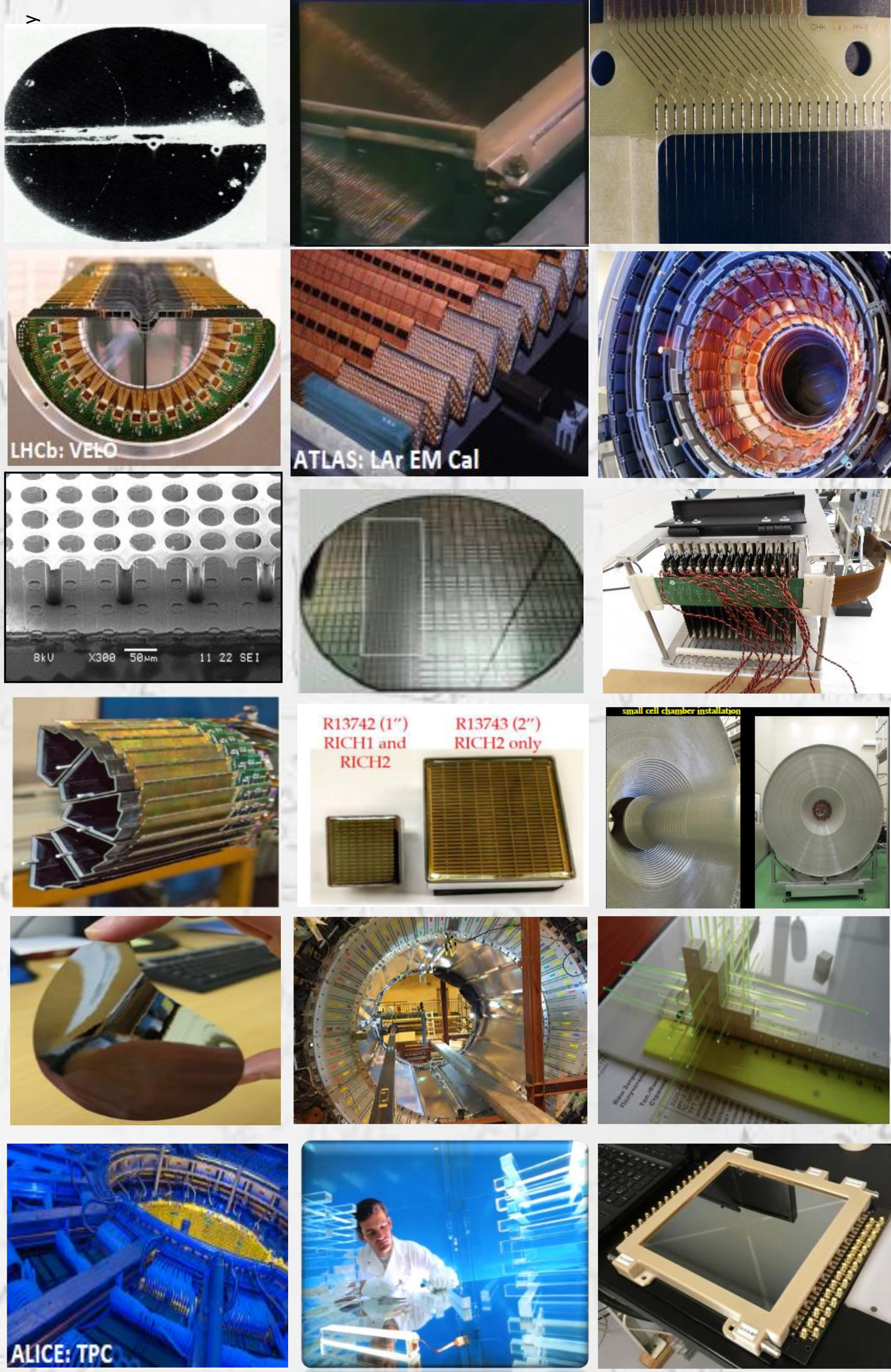




Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

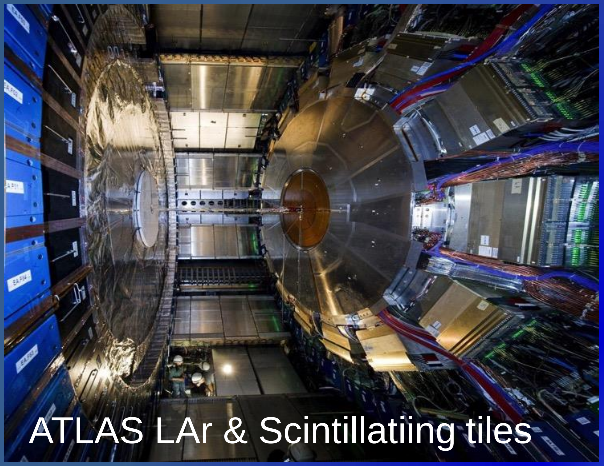
PICOSEC Micromegas

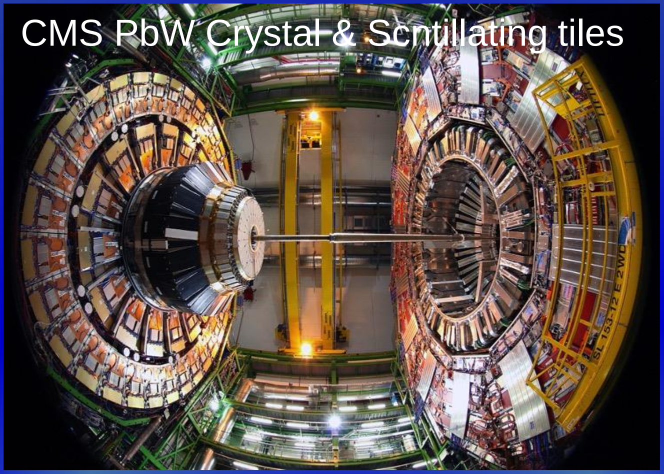
σ ~ 25 ps timing resolution (per track)

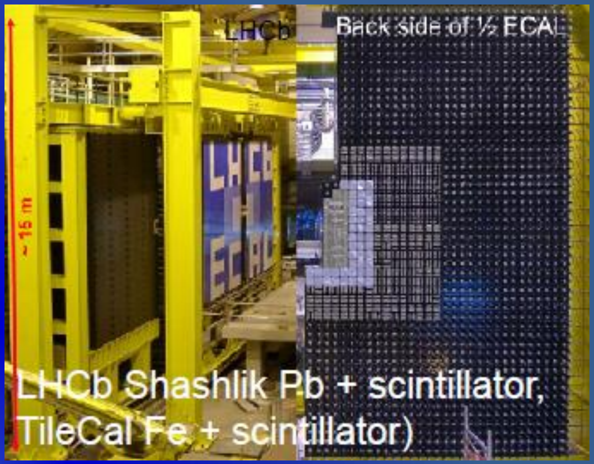


- Particle Interactions with Matter
- "Classic" Detectors (historical touch...)
- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

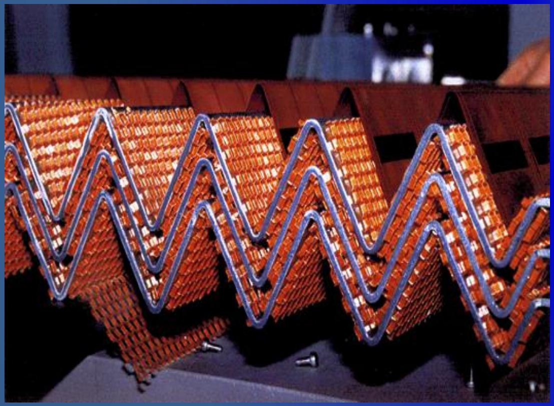
Advanced Concepts in CALORIMETRY







4 main technologies: LAr, Scintillators, Crystals (tiles or fibers), Silicon sensors



Two main concepts:

Homogeneous crystals (CsI, LYSO):
- Best possible resolution
- Application to PET

Sampling:
- Imaging: Particle Flow Algorithm
- Dream: Dual readout
- Sampling with Crystals, shashlik-type

Two main approaches for improving jet energy resolution:

Dual (or triple) readout, e.g. DREAM (FCC-ee, CePC) improvement of the energy resolution of hadronic calorimeters for single hadrons:

Cherenkov light for relativistic (EM) component
Scintillation light for non-relativistic (hadronic)

Particle flow algorithm and imaging calorimeters (CALICE detectors for ILC, CLIC, CMS HGCAL):
→ Precise reconstruction of each particle within the jet (reduction of HCAL resolution impact)

Calorimeter Concepts: Basic Principles

Two types calorimeter concepts: Homogeneous and Sampling (both EM and HAD)

Homogeneous calorimeter

It uses **a high-density material** where the shower is generated **and produces the signal**

Some typical materials

BGO, PbWO... → Scintillation
Lead Glass → Cherenkov light

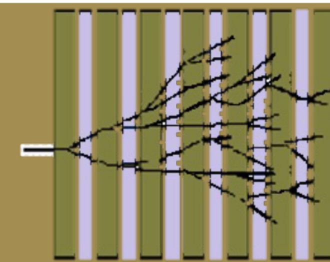
Advantages: Best energy resolution

Disadvantages: Expensive

Used only for electromagnetic calorimeters

Sampling calorimeter

It alternates **layers of high-densitity material (passive absorber)** where the shower is generated **and detectors (active planes) to produce the signal**



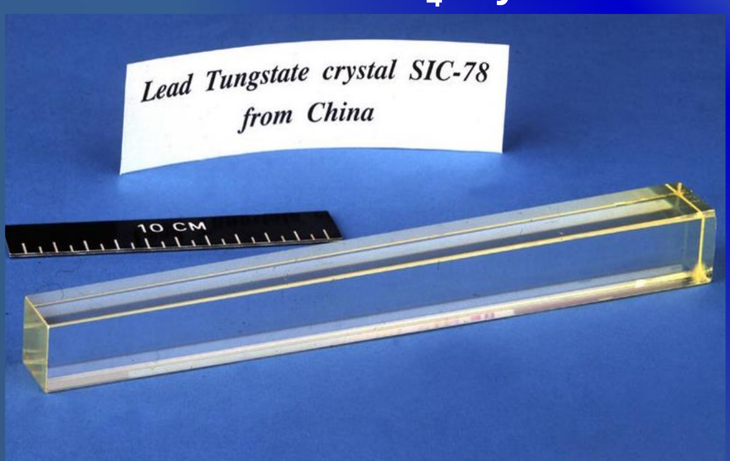
Typical absorbers: Fe, Pb, U

Typical detectors: Gaseous detectors, plastic scintillators, quartz fibers, silicon detectors noble liquid ionization chambers...

Advantages: Cheap absorber
Optimization of absorber/sensor
Compactness

Disadvantages: Worse energy resolution due to lower energy deposition and sampling fluctuations

CMS $PbWO_4$ crystal



- EM interaction : Xo ranges from 13.8 g/cm2 for Fe to 6.0 g/cm2 for U
- H interaction : λ_I ranges from 132.1 g/cm2 for Fe to 209 g/cm2 for U
- EM Calorimeters: MANY (15-30) Xo deep
- H Calorimeters: many (5-8) λI deep

ATLAS Liquid Ar

Energy Resolution of Electromagnetic Calorimeters

Usually parameterized by
(valid both for homogeneous & sampling calorimeters & for both electromagnetic and hadronic calorimeters) :

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

$a = intrinsic\ term$
$b = constant\ term$
$c = noise\ term$

a : intrinsic resolution or term

Simplified model :
- Number of produced ions/e$^-$ pairs (or photon) N=E/w
- Detectable signal (→E) is ∝ N (N quite large)

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

c : contribution of electronics noise
+ at LHC pile up noise…

b : constant term
contains all the imperfection: dead spaces, response variation versus position (uniformity), time (stability), temperature, mis-calibration, radiation damage, ….

In a **hadronic calorimeter** there are two components

$$Signal = S_{em} + S_{had} = \mathbf{e} f_{em} E + h f_{had} E$$

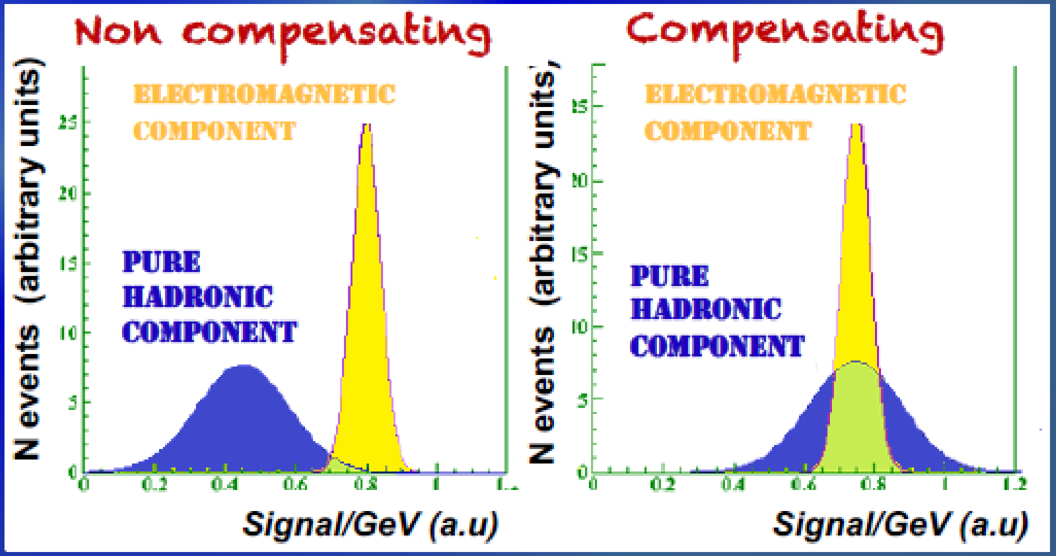
f_{em}, f_{had} = Fractions of each component

$f_{had} = 1 - f_{em}$

$\mathbf{e}, h$ = Calibration constants for each part

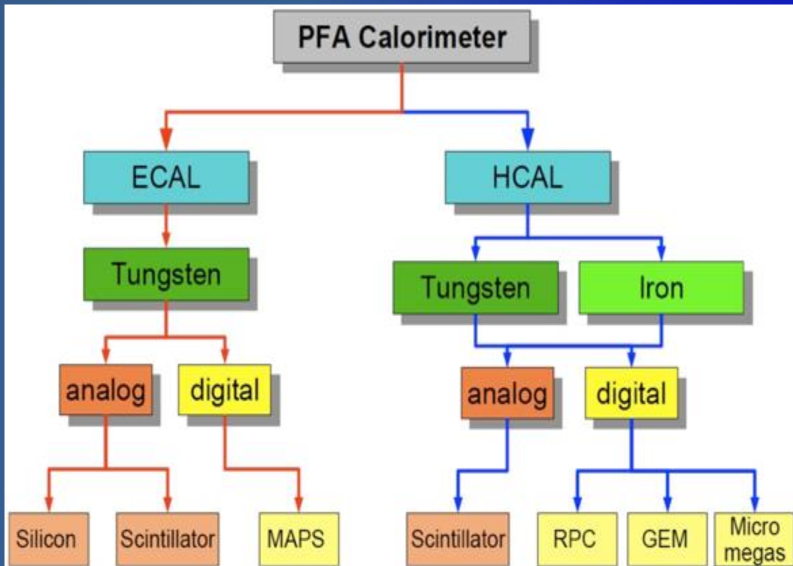
$$\frac{e}{h} = 1$$

→ Compensanting Calorimeter



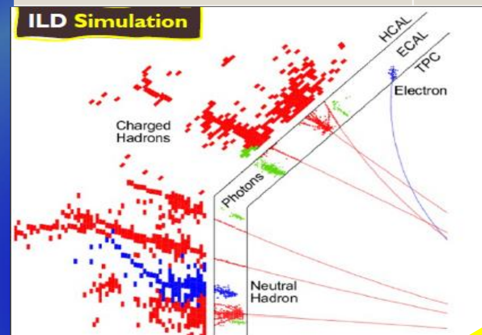
Particle Flow Calorimeters: CALICE Collaboration

Development and study of finely segmented / imaging calorimeters (PFA): initially focused on the ILC



PFA Calorimetry → reconstruct every single particle in the event

Average jet composition	PFA reconstruction
60% charged	Measured on the tracker, negligible resolution
30% photons (from π^0 decay)	Measured at ECAL ~10-20% /√(E)
10% neutral hadrons (n, K_L)	Measured at HCAL ~60-100% /√(E)



PFA reconstruction Issues:
- overlap between showers
- complicated topology
- separate "physics event" from beam-induced bkg.

Example: **ILD detector for ILC**, proposing **CALICE** collaboration technologies

	ECAL option	ECAL option	HCAL option	HCAL option
Active layer	silicon	scint+SiPM	scint+SiPM	glass RPC
Absorber	tungsten	tungsten	steel	steel
Cell size (cm×cm)	0.5×0.5	0.5×4.5	3×3	1×1
# layers	30	30	48	48
Readout	analog	analog	analog	Semi-dig (2 bits)
Depth # (X_0/Λ_{int})	24 X_0	24 X_0	5.5 Λ_{int}	5.5 Λ_{int}
# channels [10^6]	100	10	8	70
Total surface	2500	2500	7000	7000

MATURED (CALICE):
- **SiW-ECAL**
- **SciW-ECAL**
- **AHCAL**
- **DHCAL (sDHCAL)**

→ (Almost) ready for large-scale prototype
→ Prepare for quick realization of 4-5 years to real detector

ADVANCED (beyond CALICE):
- **MAPS ECAL**
- **Dual-readout ECAL**
- **LGAD ECAL (CALICE)**

→ Evaluate additional physics impact to ILC experiment
→ Needs intensive R&D effort to realize as real detector

Calorimeter Technologies at Glance (Developed for ILC)

SILICON BASED SANDWICH CALORIMETERS SI-W ECAL

Absorber: Tungsten
Sensor: Silicon
Readout: Pads 5x5 mm^2
Higgs Factories / Luxe

Narrow showers
- Better separation of particles in the transverse direction
- Compact design

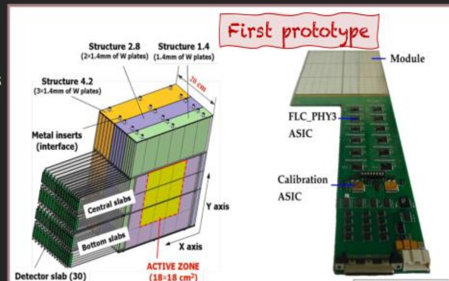
Tungsten: $X_0 = 3.5$ mm, $\rho_M = 9$ mm, $\lambda_I = 95$ mm

OPTIMIZED FOR PFA

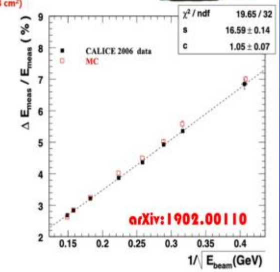
Mature technology developed by CALICE since years
Adapted also for the CMS HGCAL upgrade calorimeter

Timing information or ToF capabilities in the first layers could be achieve by replacing (part) with LGADs ~10 ps

First prototype

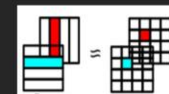


30 Layers
10K Channels
External readout



OPTICAL BASED SANDWICH CALORIMETERS: SCW-ECAL

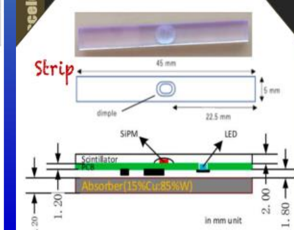
Absorber: Tungsten
Sensor: Plastic scintillator
Readout: Strips (5 x 45 mm^2)
- SiPM
Higgs Factories



(5x45 mm^2) ➔ (5x5 mm^2)

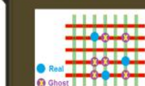
Less readout channels than SiW-ECAL

Possibility of introducing dedicated timing layer(s)

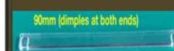


Cheaper 👍 (plastic and electronics)

Ghosts 👎

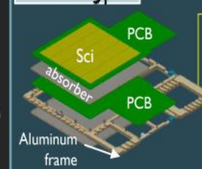


Should be eliminated by double SiPM readout

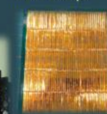


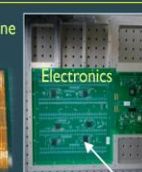
Prototype

ECAL Basic Unit (EBU)
- Scintillator strips + Hamamatsu SiPMs + SPIROC2E chips
- Tungsten-copper alloy (85:15)

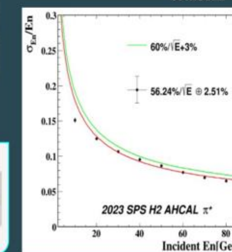


Scintillator plane
42 x 15 strips





32 EBU layers ~23 X_0
6720 readout channels
192 SPIROC2E chips



OPTICAL BASED SANDWICH CALORIMETERS: AHCAL

Absorber: Stainless steel (*)
Sensor: Plastic scintillator
Readout: Tiles (3 x 3 cm^2)
- SiPM
Higgs Factories

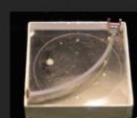
(*) Tungsten also tested for CLIC

Mature technology developed by CALICE since years
Adapted also for the CMS HGCAL upgrade calorimeter

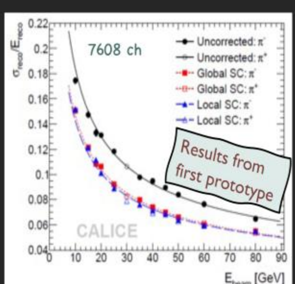
Many technical developments after the first prototype used as a probe of concept

First prototype

1 plane.
Diferent sizes:
3x3cm2 (30x30 cm2 core)
6x6cm2 12x12 cm2 (external)



Old Tile design



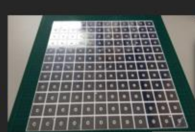
SC= Software Compensation

New Developments

Single Tile design

Individually wrapped in refective foil

Glued one by one
Light Tightness 👍
Dead areas between tiles 👎



Megatile design

Large scintillator plate with optically separated trenches filled with reflective TiO2

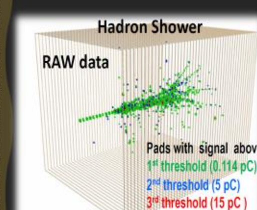
Plate wrapped in reflective foil
Easier assembly and no dead areas 👍
Not fully light tight 👎

GAS BASED SANDWICH CALORIMETERS SDHCAL

M.C. Fouz

Absorber: Stainless steel
Sensor: RPC
Readout: PADs 1x1cm²
Semi-digital Readout
Higgs Factories

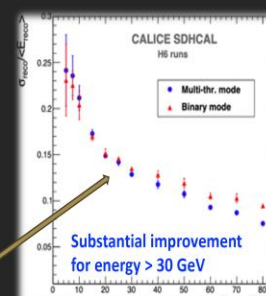
SDHCAL ~1.3m³ prototype
At Test Beam @ CERN



- 48 layers (~6λ_I)
- 1 cm x 1 cm granularity
  3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure (<500 µm deformation)

Technology under development by CALICE since more than 10 years

Advantage of semi-digital vs digital
➔ Multi-threshold improves resolution



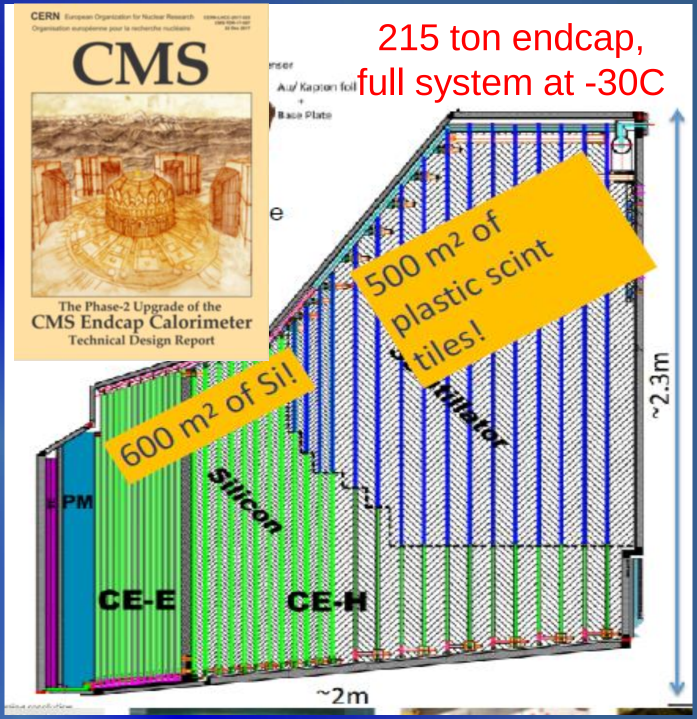
CMS High Granularity Calorimeter for Phase II Endcap Upgrade

CMS endcap region:
- PbWO4 crystal transmission loss due to radiation damage
- Worsening energy resolution due to increased pileup

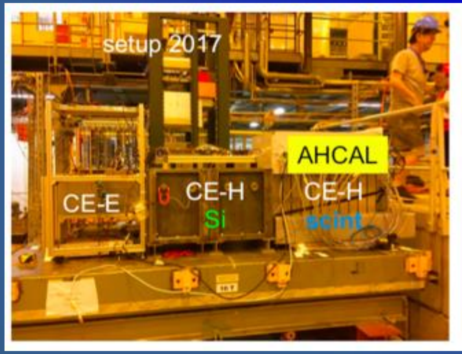
- ✓ Build a fine segmented 'particle flow' calorimeter, ECAL + HCAL combined.
- ✓ Use Si sensors as long as radiation and particle flow requires, then switch to cheaper scintillator tiles + SiPM (à la CALICE). (27000 Si-modules, 6M Si-channels, 400000 SiPMs)

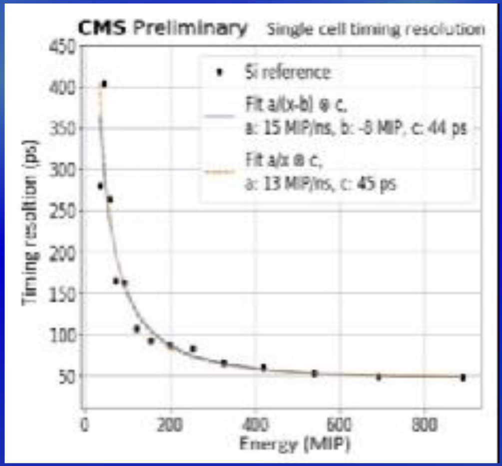
- CE-E: Si, Cu, CuW,Pb absorbers, 28 layers, 25 X0 & ~1.3λ
- CE-H: steel absorbers, 24 layers, ~8.5λ

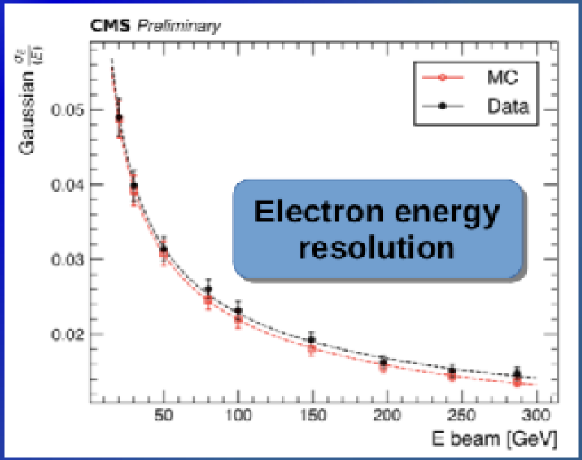
- ✓ Si pad sensors from 8'' wafers. Different sensor geometries and thicknesses (300,200,120 μm); fluences 2×10^{14} - 10^{16} n_{eq}/cm^2



New (combined) CMS HGCAL + ILC AHCAL test-beam results:
- 28 EM layers, 12 Si-HAD layers,
- 39 Sci-layers from CALICE AHCAL







Multi-layer measurements of shower signal allows precise ToF estimate of e/γ/h0 : ~ 50 ps has been achived in Si for S/N >20

R&D for ALICE FOCAL – MAPS based SiW ECAL

FOCAL (FORWARD CALORIMETER) ALICE

$3.4 < \eta < 5.8$

ALICE

HiLumi HL-LHC PROJECT

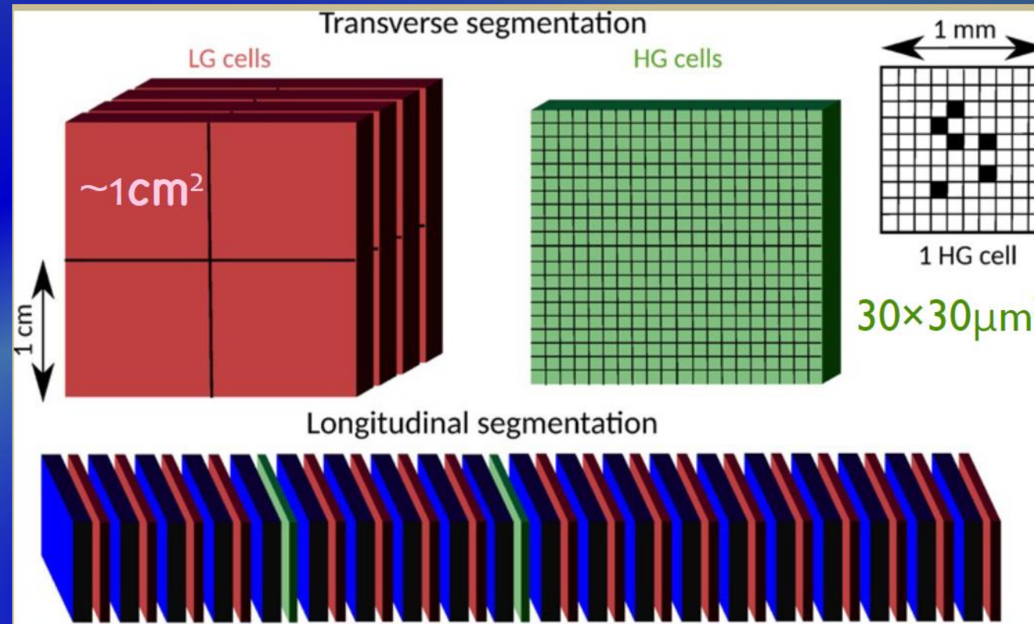
FoCal-E detector Si+W:

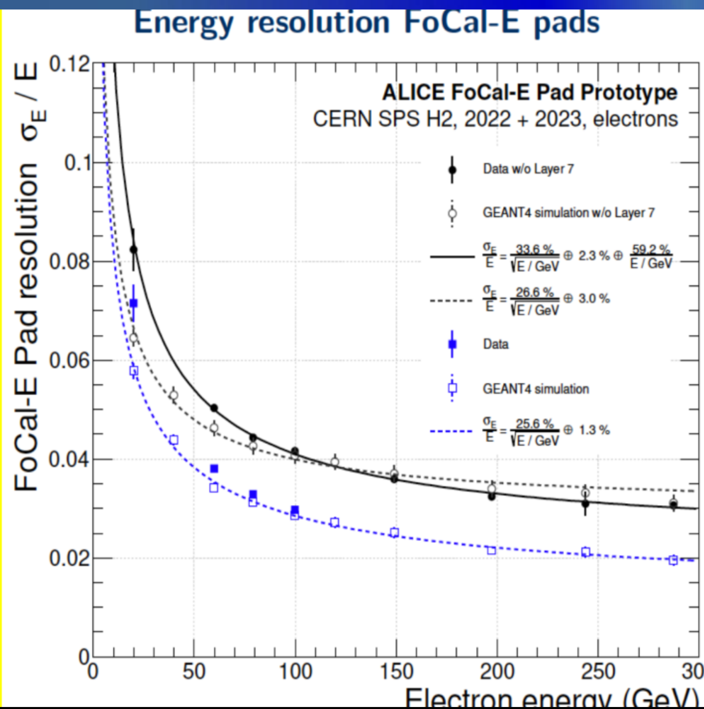
- 28 Pad layers, $1\,cm^2$
- 2 Pixel layers - MAPS (layers 5 & 10) $30\times30\mu m^2$ digital readout

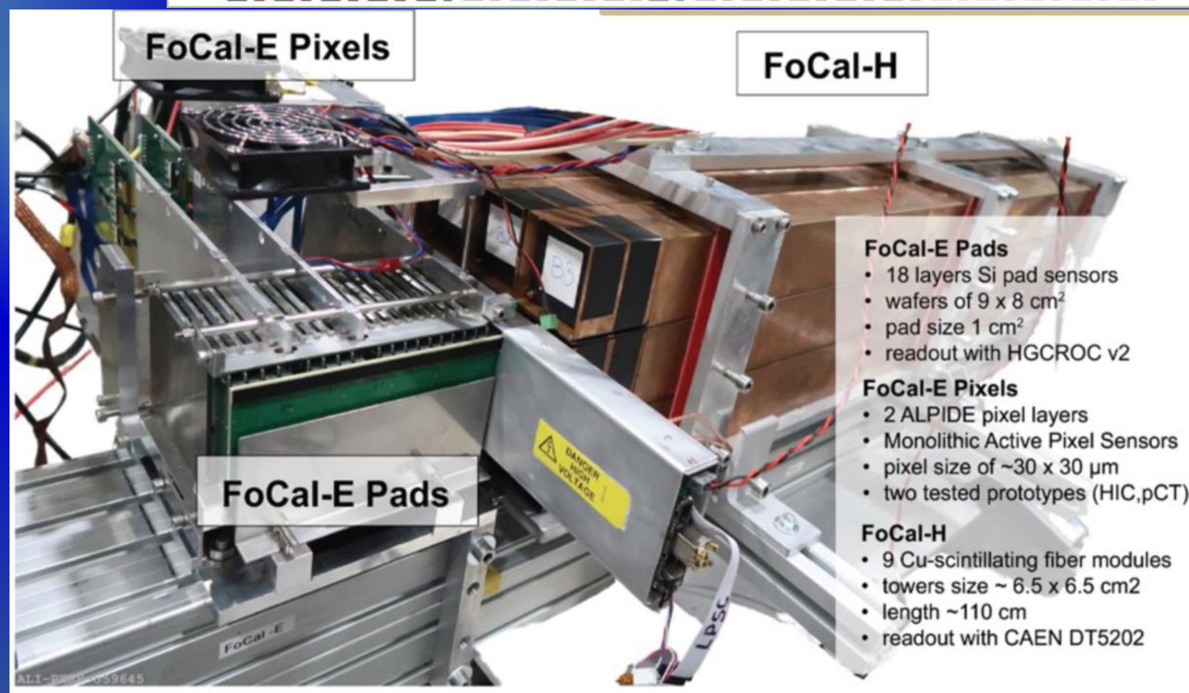
Test Beam

Monolithic Active Pixel Sensors (MAPS) with digital readout:

Fine granularity of pixels (better separation of showers)







DREAM (Dual REAdout Module): High Resolution HCAL

Cherenkov fibres

Scintillating fibres

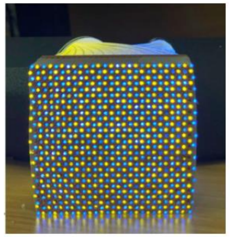
Fast signals

for relativistic (EM) component

Slow signals

for non-relativistic (hadronic)

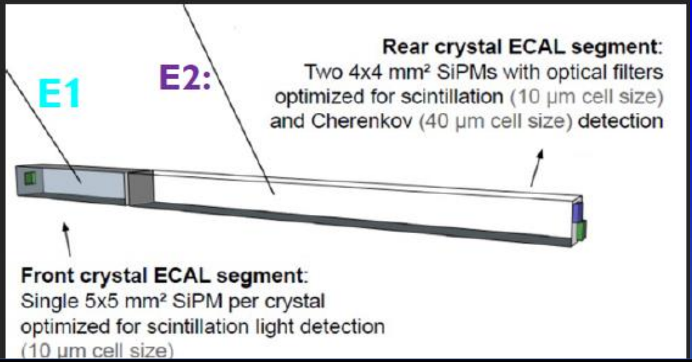
Building Blocks:



SiPM for much Better separation of Cherenkov &. scintillation light

Dual readout to capture Electromagnetic and hadronic components of shower

Scintillator and Cherenkov from the same active medium, disentangle using optical filters

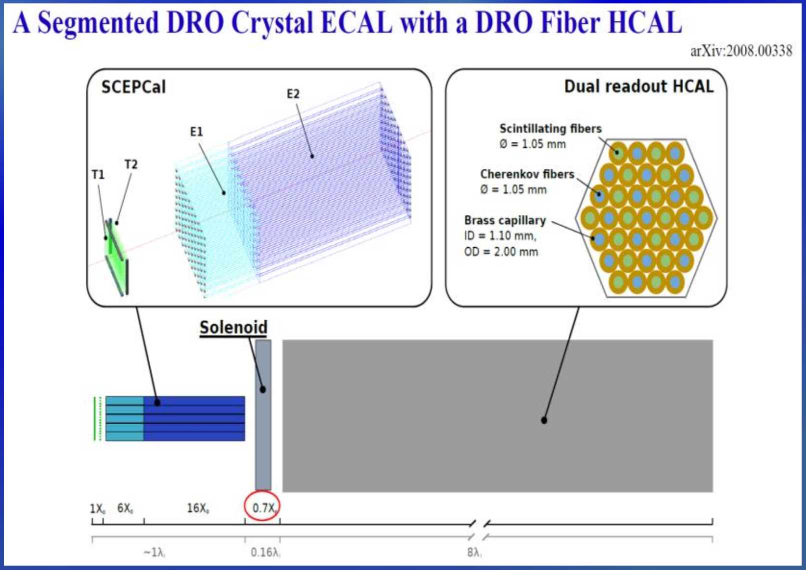


Simultaneous Detection of Cherenkov & Scintil. light:

Hadron showers :
- EM component (π^o s)
- Non-EM component (mainly soft π)

} ***Response is different (e/h ≠ 1)***

- *Cherenkov light almost exclusively produced by electromagnetic component (80% of hadronic component is non relativistic)*
- ***RECIPE:* determine electromagnetic component event by event by *comparing Č and dE/dx signals* → correct response**
- ***e/h ratio is very different for Quartz and Scintillator measurements of energy:***
  → Use Quartz fibers to sample EM component (~only!), in combination with Scintillating fibers



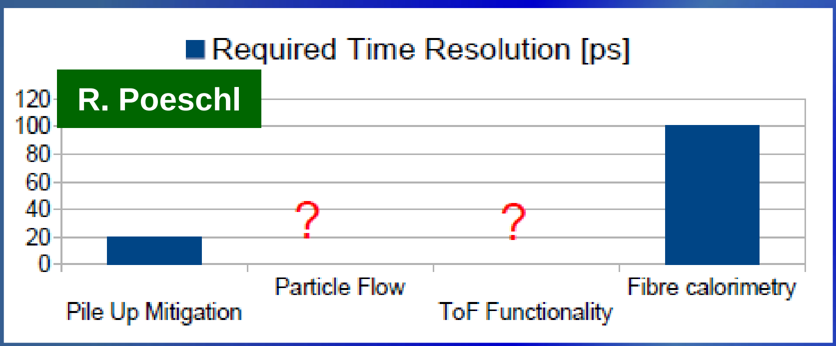
R&D Focus :
Optimize readout technologies for scintillation and Cherenkov signals – includes minimization of material between crystals to maximize sampling (-> homogeneous calorimeter)

Particle Flow (Imaging) Calorimeters: The 5th Dimension ?

Impact of 5D calorimetry (x,y,z, E, time) needs to be evaluated more deeply to undertand optimal time acc.

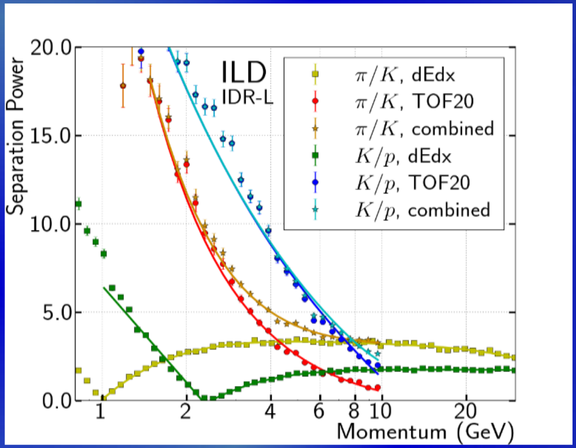
What are the real goals (physics wise)?

- *Mitigation of pile-up (basically all high rates)*
- *Support for full 5D PFA → unchartered territory*
- *Calorimeters with ToF functionality in first layers?*
- *Longitudinally unsegmented fibre calorimeters*



Replace (part of) ECAL with LGAD for O(10 ps) timing measurement

20 ps TOF per hit can separate π/k/p up to 5-10 GeV



T. Suehara @ILCX2021

Test beam at Tohoku
October 2021

Timing resolution
Is affected by noise

Sensor	Amp. th.	Time reso.
S8664-50K (inverse)	20 mV	123 psec
	40 mV	63 psec
S2385 (normal)	20 mV	178 psec
	40 mV	89 psec

✓ **The added value of ps-timing information is well recognized:**

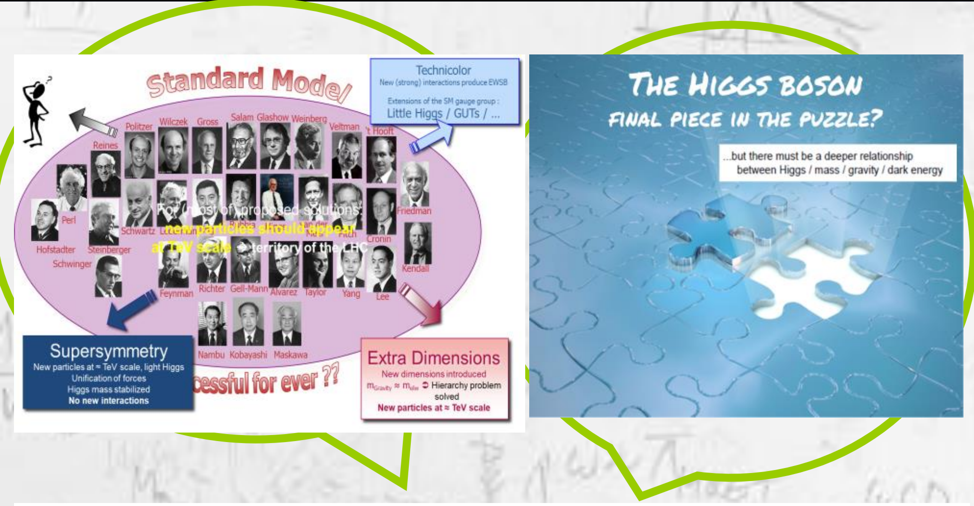
→ *Gain in scientific return to be quantified (Tracking PID, CaLO PID, Shower development)*

✓ **Trade-off between power consumption & timing capabilities (maybe higher noise level)**

→ *Timing in calorimeters / energetic showers?*

→ *Intelligent reconstruction using O(100) hits & NN can improve "poor" single cell timing*

→ *can help to distinguish particle types: usable for flavour tagging (b/c/s), long-lived searches (decaying to neutrals), enhance s(E) / E …*



Wide Choice of Detector Technologies to Reveal the SM Secrets

- Advancing Concepts Tracking Detectors: Gaseous Detectors
- Advancing Concepts Tracking Detectors: Silicon / Pixel Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification (PID) & Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing

Summary of Particle Detector Physics Lectures

The progress in experimental particle physics was driven by the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies:

- ✓ The detrimental effect of the material budget and power consumption represents a very serious concern for a high-precision silicon vertex and tracking detectors;
- ✓ CMOS sensors offers low mass and (potentially) radiation-hard technology for future proton-proton and electron-positron colliders;
- ✓ MPGDs have become a well-established technique in the fertile field of gaseous detectors;
- ✓ Several novel concepts of picosecond-timing detectors (LGAD, LAPPD) will have numerous powerful applications in particle identification, pile-up rejection and event reconstruction;
- ✓ The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method;
- ✓ The integration of advanced electronics and data transmission functionalities plays an increasingly important role and needs to be addressed;
- ✓ Bringing the modern algorithmic advances from the field of machine learning from offline applications to online operations and trigger systems is another major challenge;
- ✓ The timescales spanned by future projects in HEP, ranging from few years to many decades, constitute a challenge in itself, in addition to the complexity and diversity of the required R&D.

Replacing OUTLOOK …
A FEW WORDS OF INSPIRATION …

If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that *all things are made of atoms —little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*
In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

– Richard Feynman

5* Scientific Discoveries of the Last Decade In Fundamental Physics

- ✓ ***Higgs Boson***
- ✓ ***Gravitational Waves***
- ✓ ***Black Hole Event Horizon***

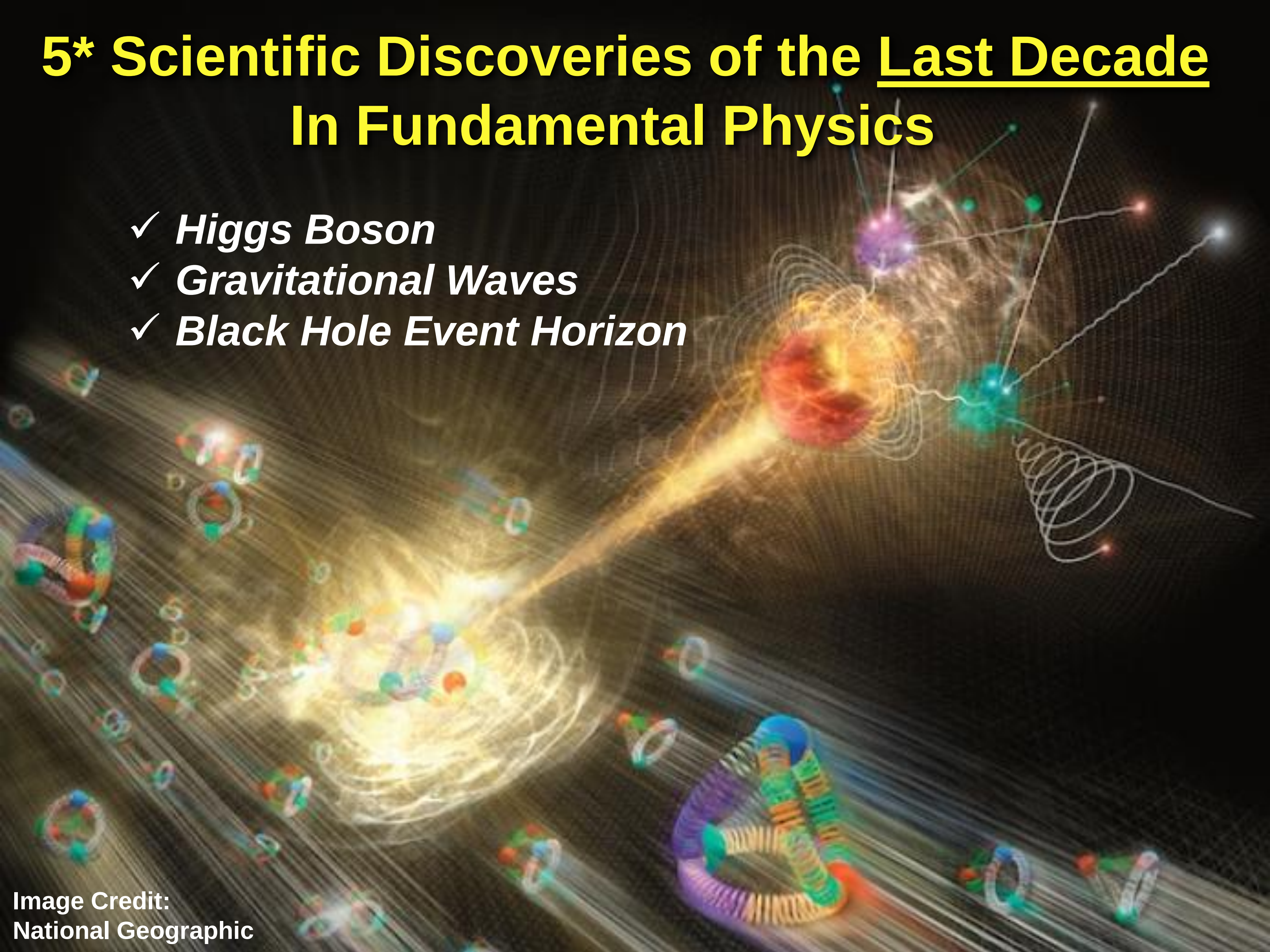


Image Credit:
National Geographic

5* Scientific Discoveries of the Last Decade In Fundamental Physics

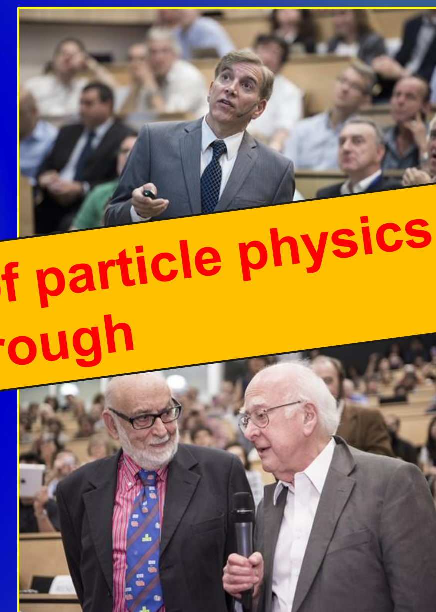
- ✓ *Higgs Boson*
- ✓ *Gravitational Waves*
- ✓ *Black Hole Event Horizon*

We have a "virtuous cycle", which must remain strong and un-broken: from fundamental science comes applied research and technological breakthrough, enabling novel detector concepts and techniques, which in turn lead to a greater physics discoveries and better understanding of our Universe.

Image Credit:
National Geographic

Higgs Discovery at Large Hadron Collider @ CERN (2012)

"As a layman I would now say… I think we have it – It is a Discovery" (Rolf-Dieter Heuer, CERN DG)



The unique organizational structure and culture of particle physics contributed to this scientific breakthrough

Both ATLAS and CMS Collaborations have reported observation of a narrow resonance ~ 125 GeV consistent with long-sought Higgs boson

The HIGGS BOSON is part of our "origin".

We did not know on that day and still have to establish if it is – "THE HIGGS BOSON" of the SM or comes from one of the SM extensions

Gravitational Waves – LIGO Observatory (2016)

Detection by the LIGO detector of gravitational waves, or ripples in space and time, after they traveled more than a billion of light years. This confirmed a key prediction of Einstein's theory of general relativity and provided the first direct evidence that black holes merge.

M87 Black Hole – Event Horizon Telescope (2019)

What Are We Seeing in This image ?

Black Holes are "Where God Divided by Zero!"

- The first DIRECT evidence for black holes !!!
- Black holes are REALLY BLACK, consistent with GR predictions
- The bright ring comes from emission of the accretion materials

One Day at CERN in 2050 …

THE DAILY TELEGRAPH Monday.

The Daily Telegraph

News 9

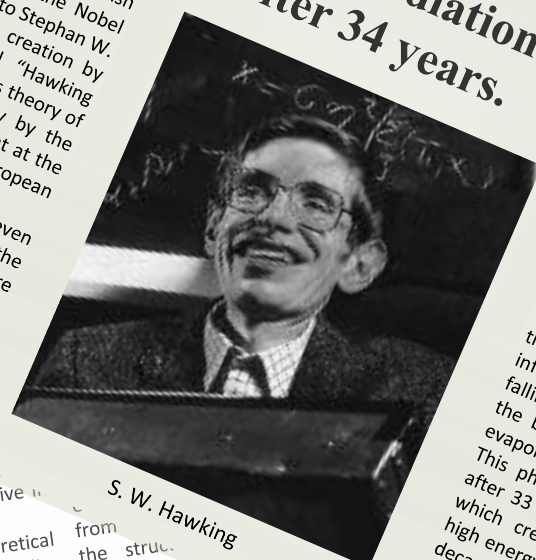
Hawking's "luminous" victory!

Stephen Hawking's black hole radiation theory is proven experimentally at CERN after 34 years.

CAMBRIDGE, 17 November: The Sweedish Royal Academy has announced that the Nobel Price in Physics for this year will go to Stephan W. Hawking for his theory of particle creation by black holes, which is also named "Hawking radiation" after its founder. Hawking's theory of black hole decay was proved recently by the famous black hole production experiment at the LArge Hadron Collider (LHC) of CERN (European Center for Nuclear REsearch.

Black holes are such objects from which even light cannot escape. Since lightspeed is the ultimate speed in universe, black holes are objects from which no escape is possible. However this idea was completely changed by a revolutionary paper by Hawking published in 1975 which suggested that black holes could emit radiation via a complicated quantum mechanical process. Briefly this idea states that spacetime near a black hole is not a classical vacuum. Energy fluctuations near a black hole creates particle-antiparticle pairs among which the antiparticle with negative energy enters the black hole while the particle with positive energy flies off to infinity. Negative energy of the antiparticle falling into the black hole reduces the mass of the black hole, therefore black hole seems to evaporate and emit particles.

This phenomena was finaly observed in CERN after 33 years of its proposal in an experiment which created miniature black holes through high energy proton collisions. These black holes decayed immediately after their production, emitting a spectrum of high multiplicity of particle species.



S. W. Hawking

Late Edition
New York: Today, partly sunny then a few clouds, high 41. Tonight, increasing clouds, low 33. Tomorrow, increasing wind, high 40. Yesterday, high 40, low 29. Details, Page 38.

THREE DOLLARS

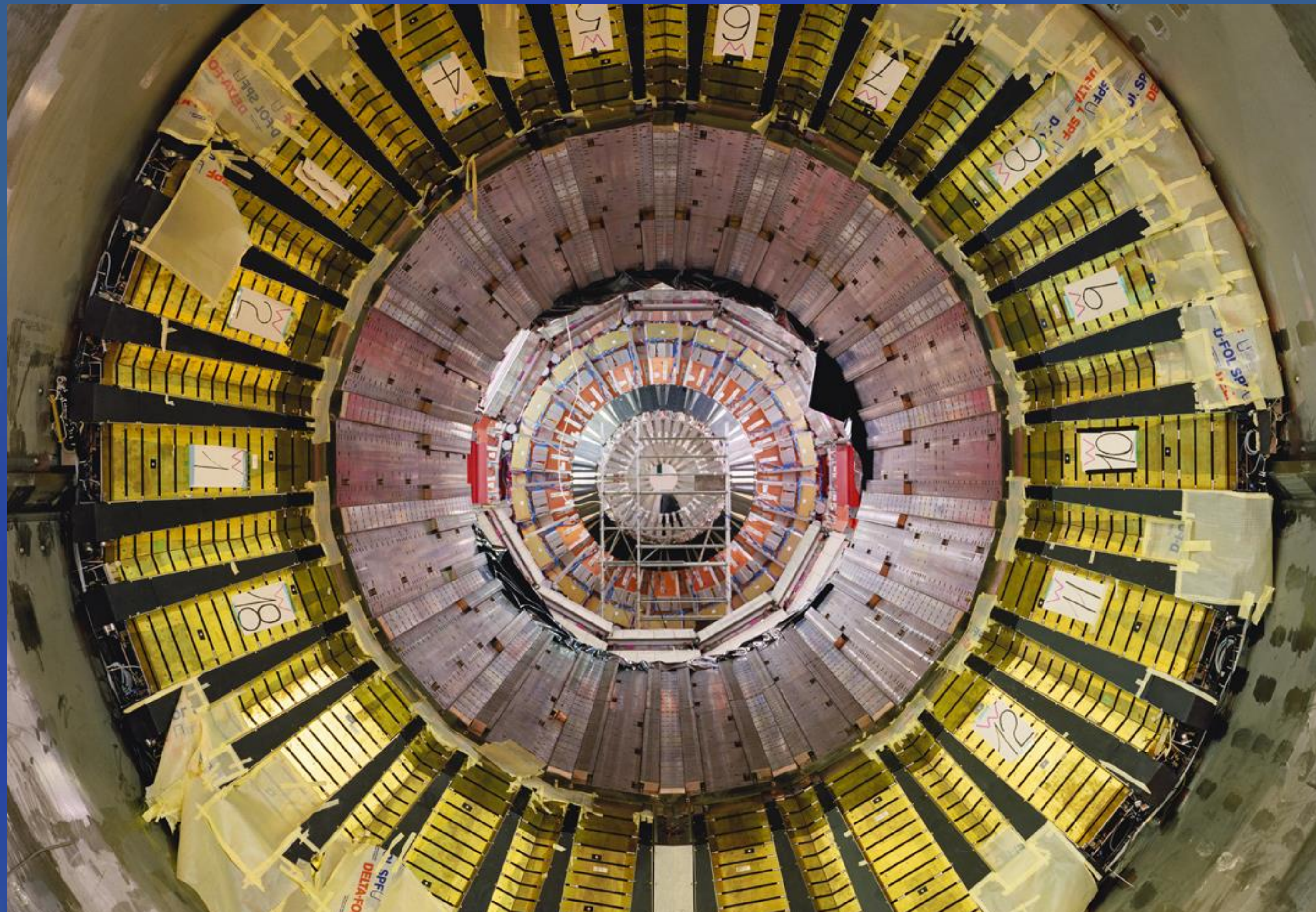
live in ... quantum m... spectrum. As... decay product... among the dat... properties to da...

fac... spaceti... Direct exp... coming from th... temperature of black... that spacetime has more... four dimensions (length, ... height and time) that we perceive i... everyday life.

In recent years, many theoretical assumptions predicted the possibility for the existence of extra dimensions in spacetime, but till now these extra dimensions were not observed since firstly they open up at only very small distance scales and secondly, the

from ... the struc... formed, the ... holes decay thr... mechanical process ... radiation abd the decay pro... be studied

Who Knows …



Knowledge is limited. Whereas the Imagination embraces the entire world…   Albert Einstein

Bridge the gap between science and society …

The Role of Big High Energy Physics Laboratories, like CERN – innovate, discover, publish, share

… in order to bring the world (a little bit) closer together