Particle Detectors II

- Physics Cases and Detector Challenges
- Particle Interactions
- Tracking Detectors
- Calorimeters
- Reconstruction and Detector Concepts

Day 1

Day 2

→ can only give an incomplete overview of existing detectors and detector technology with slight focus on LHC detectors

Tracking Detectors

- Momentum Measurement
- “Classic” Detectors (historical touch...)
- Wire Chambers
- Silicon Detectors

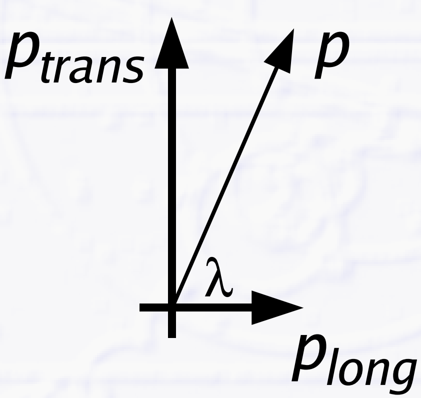
Momentum Measurement

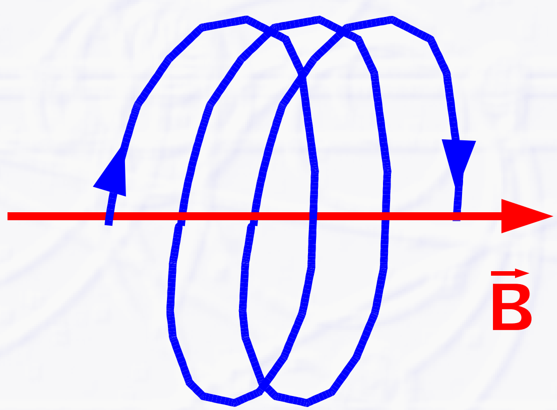
- **Charged particles are deflected by magnetic fields**
  - **homogeneous B-field → particle follows a circle with radius r**

$$p_t\,[\mathrm{GeV/c}] = 0.3 \cdot B\,[\mathrm{T}] \cdot r\,[\mathrm{m}]$$

measuement of p_t via measuring the radius

  - **this is just the momentum component ⊥ to the B-field**
    transverse momentum p_t
  - **no particle deflection parallel to magnetic field**
  - **if particle has longitudinal momentum component**
    → particle follows a helix



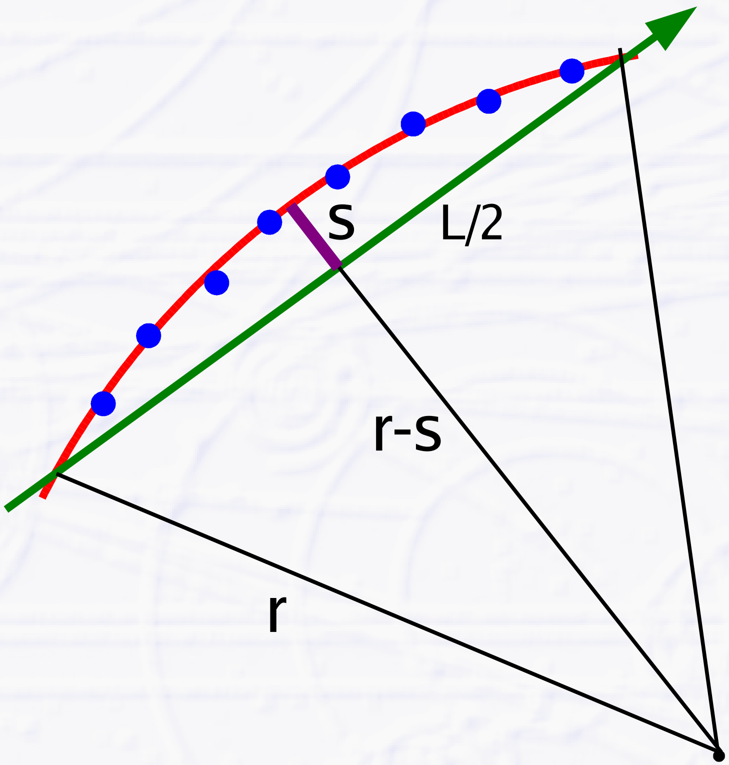


total momentum p to be measured via dip angle λ

$$p = \frac{p_t}{\sin\lambda}$$

Sagitta Error *(the Gluckstern formula)*

- **How to measure the radius?**
  - **tracking detectors measure the position of the track on various points along the circle**



from good old bubble chamber days:
measure the sagitta of the track

$$r = \frac{L^2}{8s} + \frac{s}{2} \qquad \text{if } s >> L \qquad r \approx \frac{L^2}{8s}$$

R.L. Gluckstern, NIM 24 (1963), 381

sagitta/radius is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$

sagitta error $\sigma_s = \sqrt{\frac{A'_N}{N+4}} \frac{\sigma_{r\phi}}{8}$ with statistical factor $A'_N = 720$

relative transverse momentum resolution σ_{pt}/p_t

$$\frac{\sigma_{p_t}}{p_t} = \frac{8\,p_t}{0.3\,B\,L^2} \cdot \sigma_s \quad \Rightarrow \quad \frac{\sigma_{p_t}}{p_t} \propto p_t$$

Momentum Resolution

- **The (transverse) momentum resolution is dominated by two components**
  - **contribution from measurement error** $\frac{\sigma_{p_t}}{p} \propto p_t$
  - **contribution from multiple scattering (remember** $\Theta_0 \propto \frac{1}{p_t}\sqrt{\frac{L}{X_0}}$ **)**
    - **what is the consequence to the relative momentum error?**
    - **we know that**

$$\frac{\sigma_{p_t}}{p} \propto p_t \cdot \sigma_{r\phi}$$

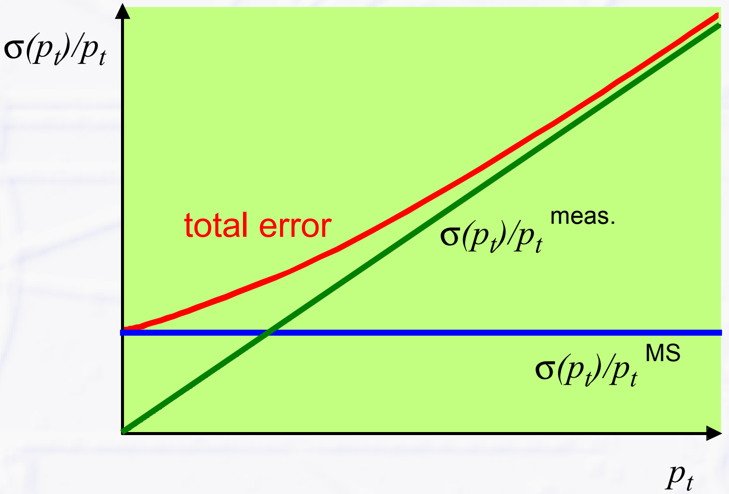
replacing point measurement error with multiple scattering error →

$$\left.\frac{\sigma_{p_t}}{p}\right|^{\text{m.s.}} \propto p_t \cdot \Theta_0 = \text{const}(!)$$

- **the multiple scattering contribution to the transverse momentum error is constant**

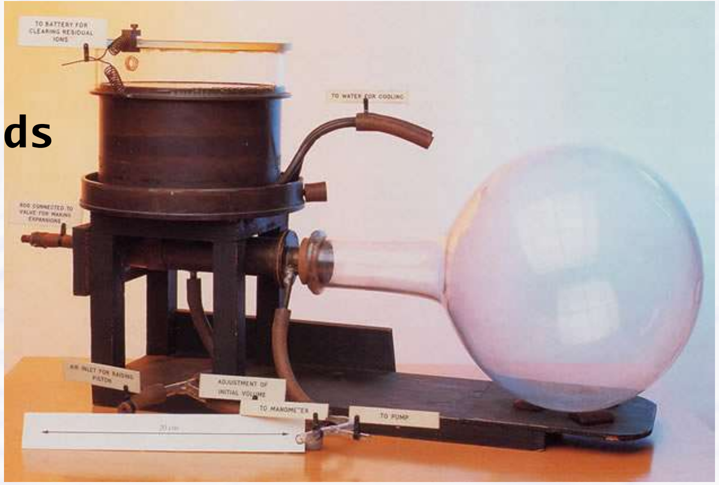
typical size of multiple scattering contribution ~0.5%

tracking detector filled with 1 bar Argon, 1 m track length



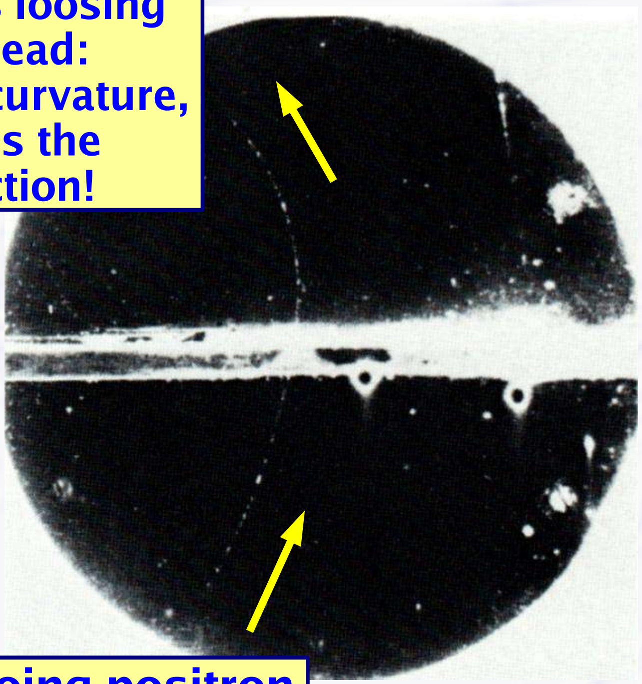
"Classic" Particle Detectors

- **Cloud chamber** (1911 by Charles T. R. Wilson, Noble Prize 1927)
  - chamber with saturated water vapour
    - originally developed to study formation of rain clouds
  - charged particles leave trails of ions
    - water is condensing aound ions
  - visible track as line of small water dropletts



UK Science Museum

positron is loosing energy in lead: narrower curvature, this defines the track direction!



LBNL Image Library

lead plate

magnetic field

upward going positron

was used at discovery of the positron
(1932 by Carl Anderson, Noble Prize 1936)

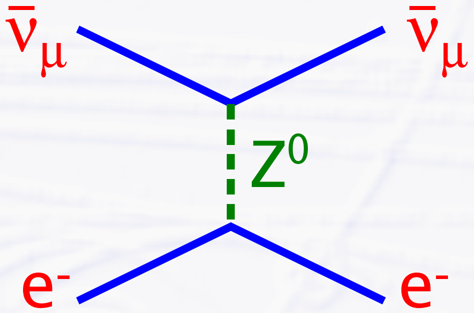
"Classic" Particle Detectors

- **Similar principle than cloud chamber:**
- **Bubble chamber** (1952 by Donald Glaser, Noble Prize 1960)
  - chamber with liquid (e.g. H_2) at boiling point ("superheated")
  - charged particles leave trails of ions
    - formation of small gas bubbles around ions

Donald Glaser

LBNL Image Library

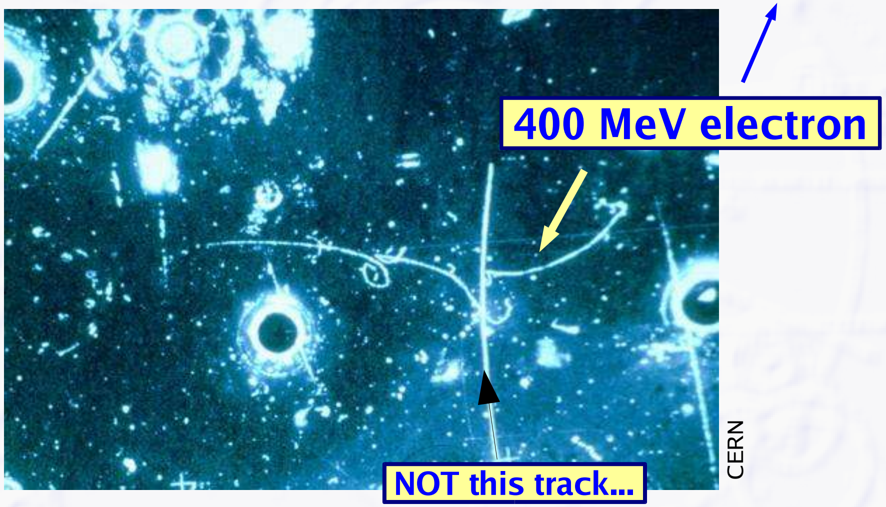
was used at discovery of the "neutral current"
(1973 by Gargamelle Collaboration, no Noble Prize yet)



Gargamelle bubble chamber

CERN

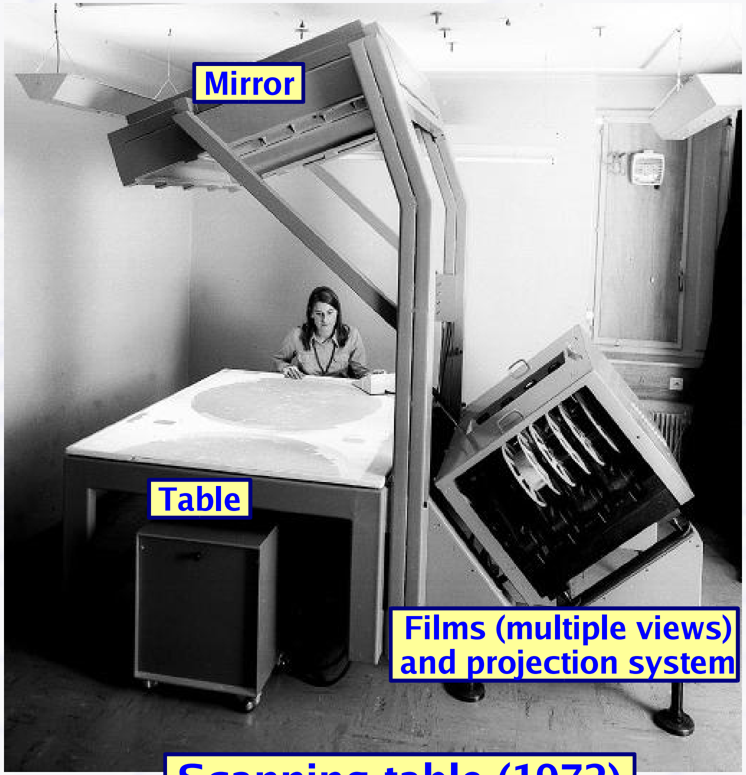
$\bar{\nu}_\mu$ →



CERN

"Classic" Particle Detectors

- **Advantages of bubble chambers**
  - liquid is
    BOTH detector medium
    AND target
  - high precision
- **Disadvantages**
  - SLOW!!!
    - event pictures taken with cameras on film
    - film needs to be developed, shipped to institutes
    - and optically scanned for interesting events
  - Need FASTER detectors (electronic!)

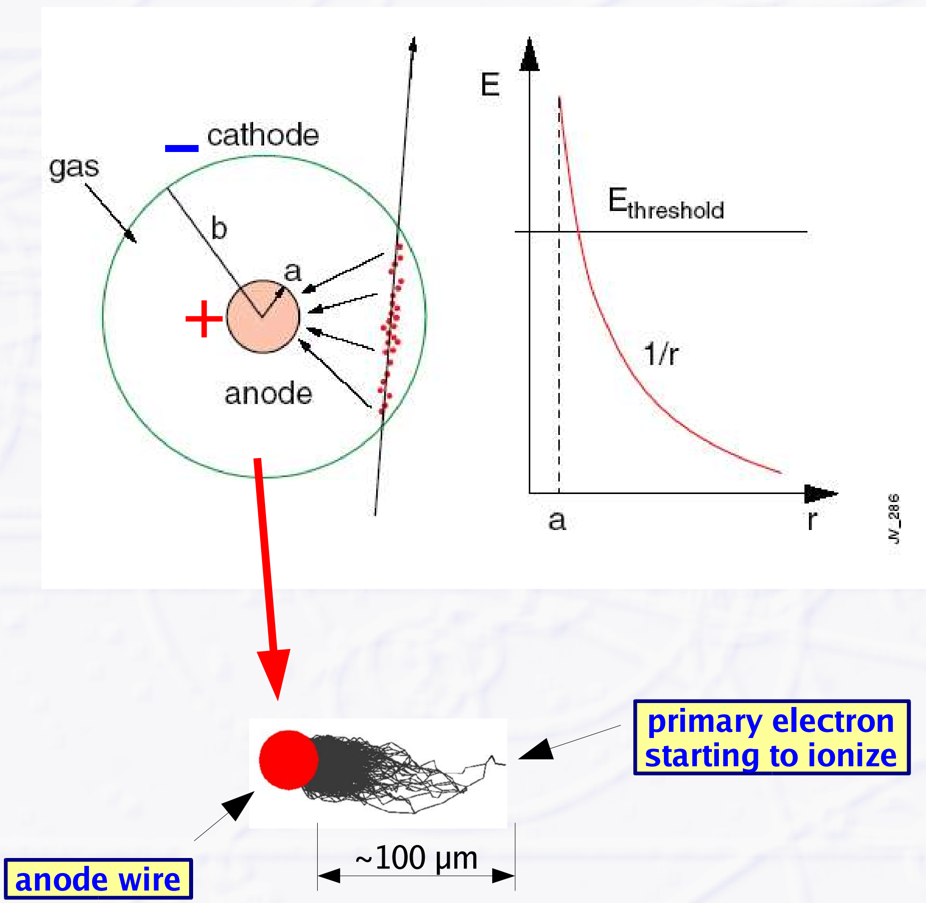


Scanning table (1972)

- **However:**
  Some important social side effects of bubble chamber era...
  - scanning often done by young "scanning girls" (students)...
  - ...who later got married with the physicists...

“Classic” Particle Detectors

- **The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)**
  - Tube filled with inert gas (He, Ne, Ar) + organic vapour
  - Central thin wire (20 – 50 µm ∅) , high voltage (several 100 Volts) between wire and tube

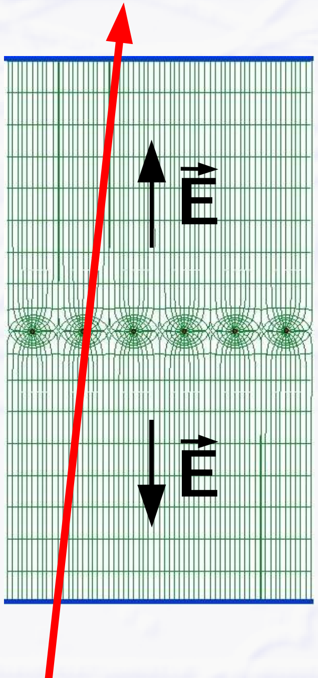


- Strong increase of E-field close to the wire
  - electron gains more and more energy
- above some threshold (>10 kV/cm)
  - electron energy high enough to ionize other gas molecules
  - newly created electrons also start ionizing
- avalance effect: exponential increase of electrons (and ions)
- measurable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

"Classic" Particle Detectors

Georges Charpak

- **Geiger-Müller tube just good for single tracks with limited precision (no position information)**
  - ➔ **in case of more tracks more tubes are needed or...**
- **Multi Wire Proportional Chamber (MWPC)**
  (1968 by Georges Charpak, Nobel Prize 1992)
  - ➔ **put many wires with short distance between two parallel plates**



cathode plane (-)

anode plane (+),
many wires,
a few mm apart

cathode plane (-)

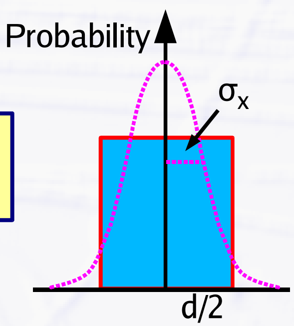
charged particle

Georges Charpak, Fabio Sauli and Jean-Claude Santiard

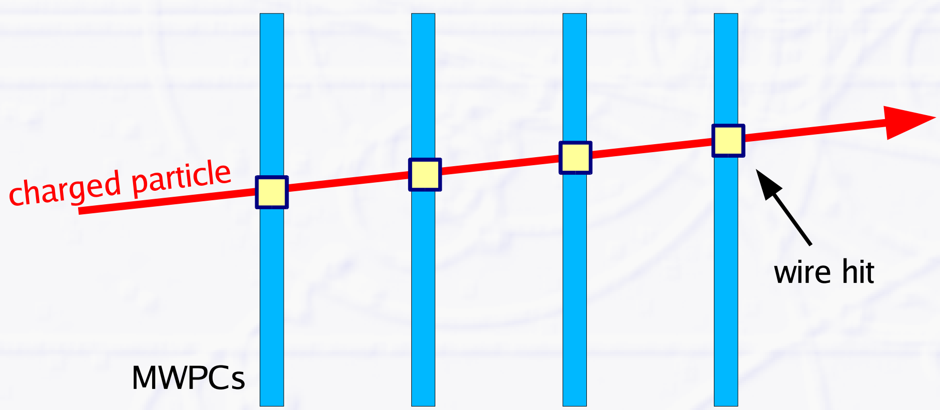
Wire Chambers - MWPC

- **Multi Wire Proportional Chamber (MWPC)**
  - was first electronic device allowing high statistics experiments
  - and with resonable resolution
- **Typically several 100 – 1000 wires, ~ 1 mm spacing**
  - if charged particle is passing the MWPC → one wire gives signal
  - resolution: $\sigma_x \approx \frac{d}{\sqrt{12}}$ e.g. for d = 1 mm → ~300 µm

we don't know where the particle went through within the 1 mm spacing = "flat" probability distribution, this is the width of an equivalent Gaussian distribution



- **If many MPWCs are put one after each other**
  - each particle creates one point per MWPC (~300 µm resolution per point)



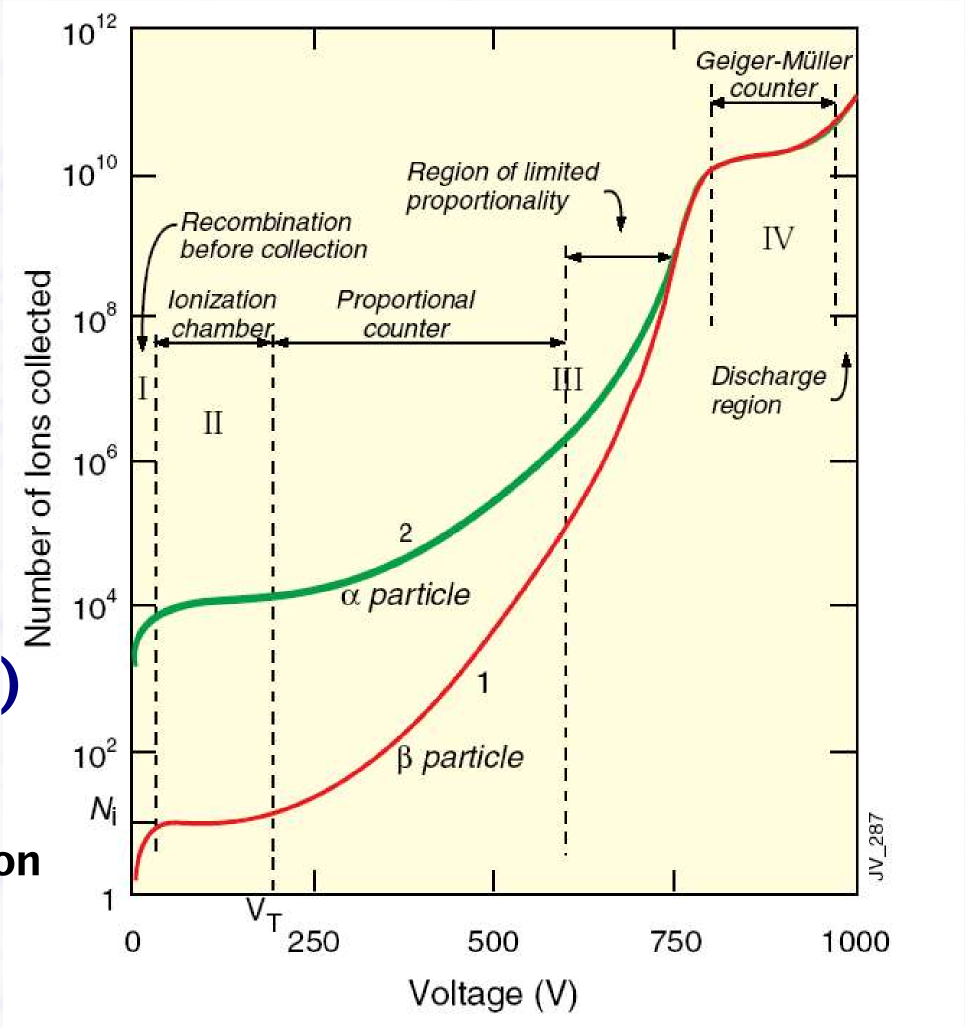
can reconstruct track with e.g. 4 points

one coordinate only, use additional MWPCs tilted by 90° to get other coordinate

Wire Chambers – Operation Modes

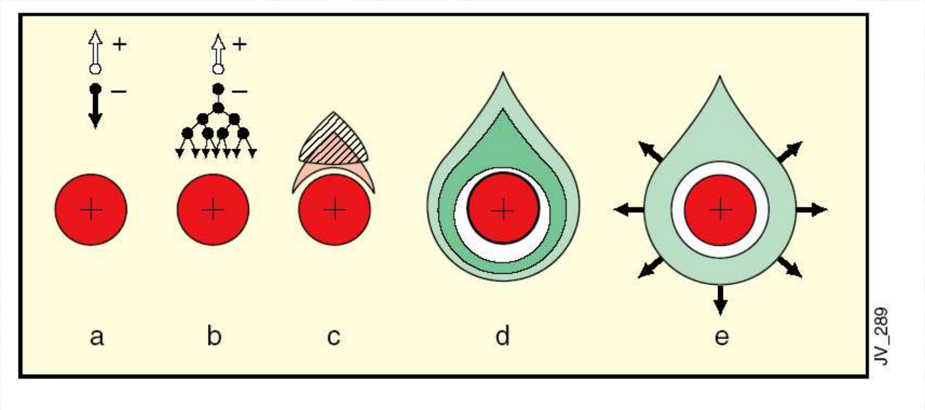
High Voltage

- **No collection (I)**
  - ions recombine before collected
- **Ionization Mode (II)**
  - ionization charge is fully collected, no charge multiplication yet
  - gain ~ 1
- **Proportional Mode (IIIa)**
  - gas multiplication, signal on wire proportional to original ionization
  - gain ~ 10^4
- **Limited Proportional Mode (IIIb)**
  - secondary avalances created by photoemission from primary avalances, signal no longer proportional to ionization
  - gain ~ 10^{10}
- **Geiger Mode (IV)**
  - massive photoemission + discharge, stopped by HV breakdown



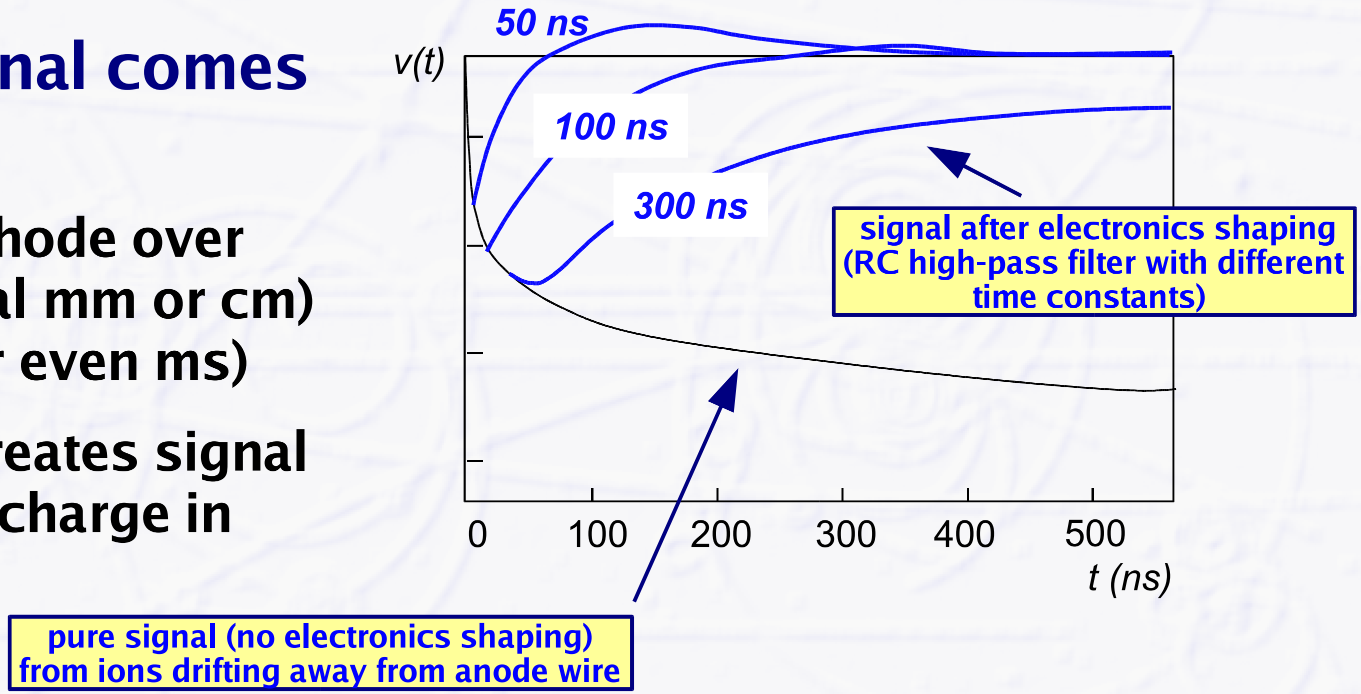
Wire Chambers – Signal Formation

- **Signal formation is DIFFERENT to what you may think of**



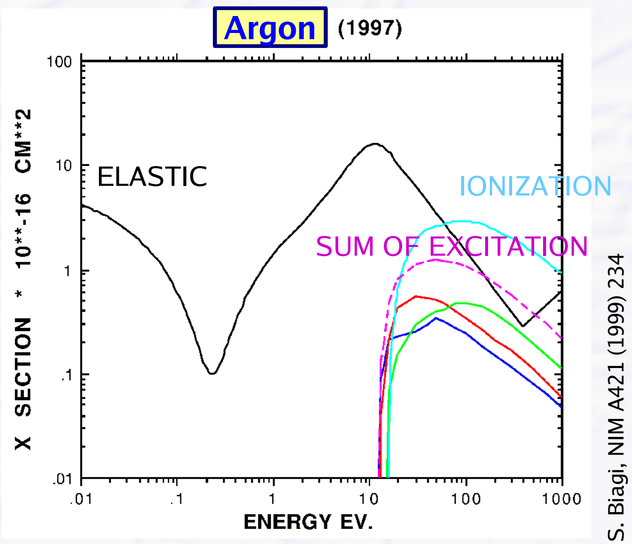
- Electrons from avalance are collected within a very short time (few ns)
- Contribution of electrons to wire signal is rather small (few % only)

- **Main part of the signal comes from the IONS**
  - Ions drift back to cathode over long distance (several mm or cm) and time (many μs or even ms)
  - Moving ion charge creates signal via influence (mirror charge in conductor)

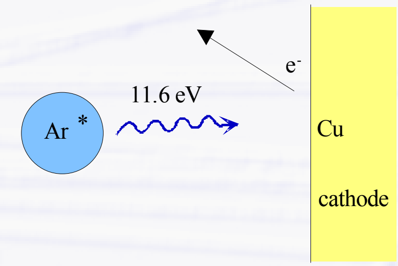


Wire Chambers - Quenching

- **Slight problem in gas avalance**
  - Argon atoms can be ionized but also can be brought into excited states
  - Exited Argon atoms can only de-exite by emission of high-UV photons

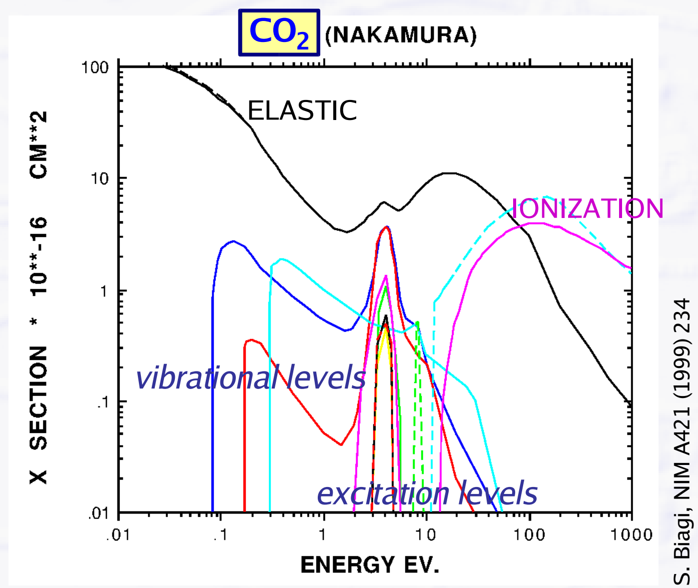


consequence: UV photons (>11.6 eV) hit surface of metals (cathode) and free new electrons, ionization energy of Cu = 7.7 eV



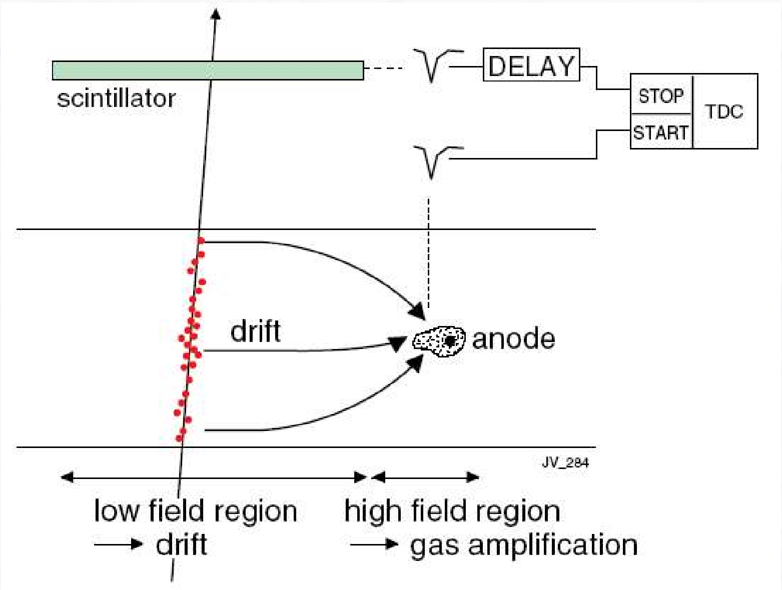
VERY unstable operation

- **Solution**
  - Add gases with many vibrational and rotational energy levels: CO_2, CH_4
  - Absorption of UV photons over a wide energy range; dissipation by collisions



Wire Chambers – Drift Chambers

- **Resolution of MWPCs limited by wire spacing**
  - **better resolution → shorter wire spacing → more (and more) wires...**
    - **larger wire forces (heavy mechanical structures needed)**
    - **(too) strong electrostatic forces when wires too close to each other**
- **Solution**
  - **obtain position information from drift time of electrons**
    - **drift time = time between primary ionization and arrival on wire (signal formation)**



start signal (track is passing drift volume) has to come from external source: scintillator or beam crossing signal

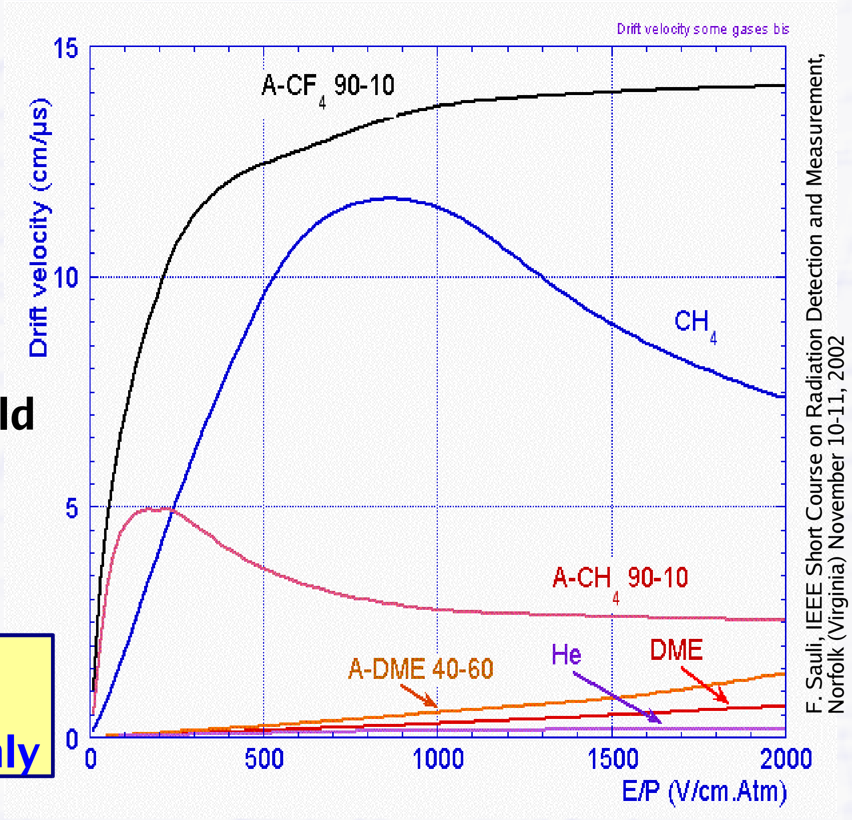
- **Need to know drift velocity v_D to calculate distance s to wire**
  (= track position within the detector)

$$s = \int_{t_{start}}^{t_{stop}} v_D \, dt$$

Wire Chambers – Drift Velocity

- **Large range of drift velocities in gases: 1 .... 10 cm/μs**
  - for a certain mixture
    - depends on electrical field and gas density (pressure)
- **Typical categories**
  - "slow" gases, e.g. CO_2 mixtures
    - 1-2 cm/μs, almost linear dependence on E-field
  - "fast" gases, e.g. CF_4 mixtures
    - ~10 cm/μs or more

LHC detectors need fast gases = short drift time to collect all electrons until next bunch crossing (25 ns) or at least within a few bunch crossings only



  - "saturated" gases, e.g. CH_4 mixtures
    - have maximum of drift velocity at certain E-field
    - widely used: Ar/CH_4 (90/10)

variety of gases allows multiple combinations: lots of *black magic!*

gases with drift velocity maximum are rather convienient: drift velocity less sensitive to E-field variations and almost constant

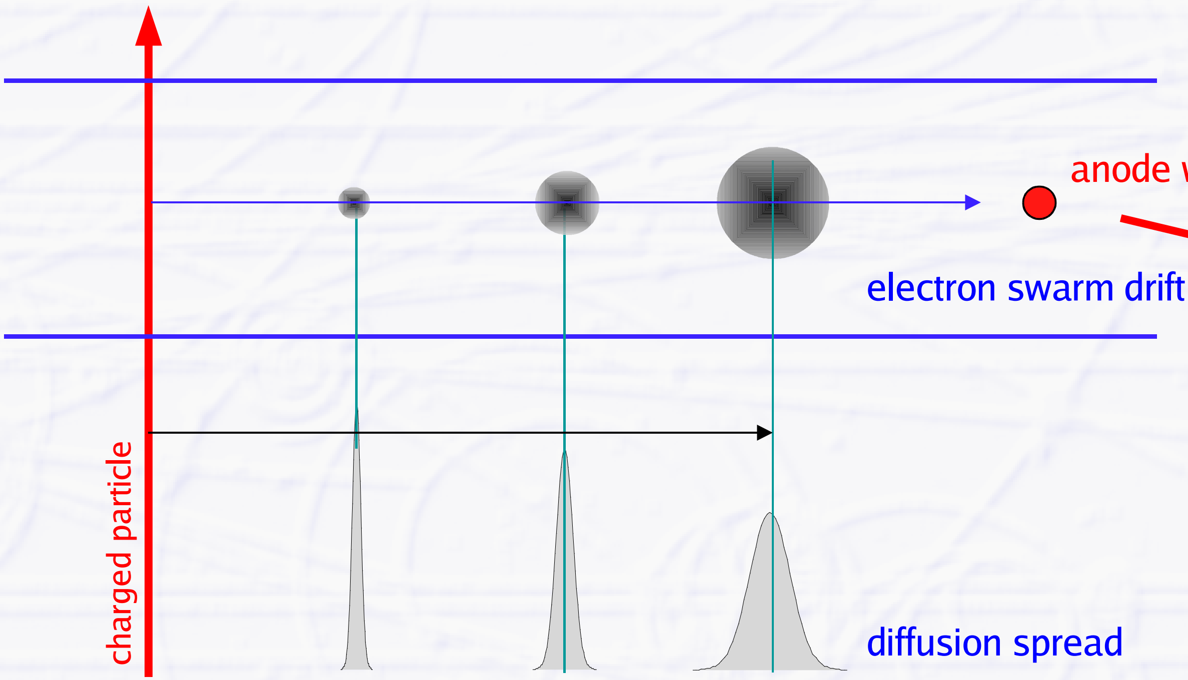
Wire Chambers - Diffusion

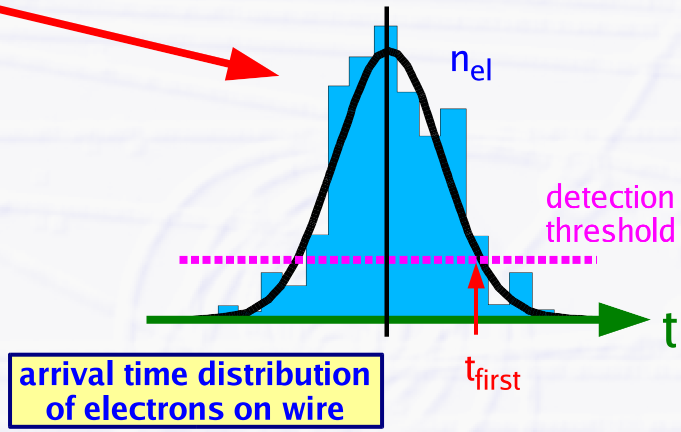
- **Electrons scatter with the gas molecules on their way to the wire (diffusion)**
  - **"thin" ionization trail gets broader**

$$\sigma_x = \sqrt{2 D_l t}$$

diffusion spread

longitudinal diffusion constant





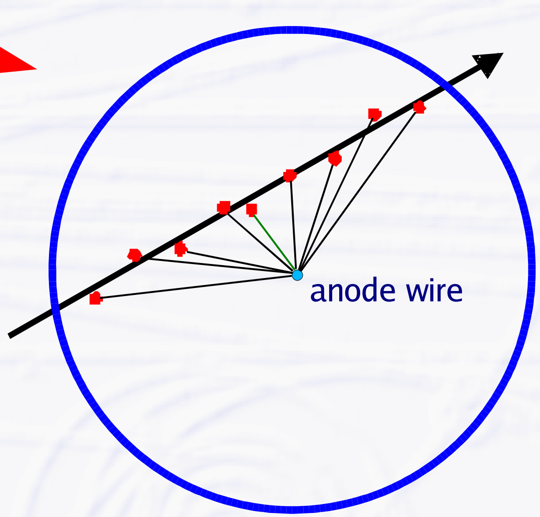
- **Measured drift time is arrival time of "first" electron (above detection threshold)**
  - **if "no" threshold (unlimited sensitivity)**

$n_{el} = 100$

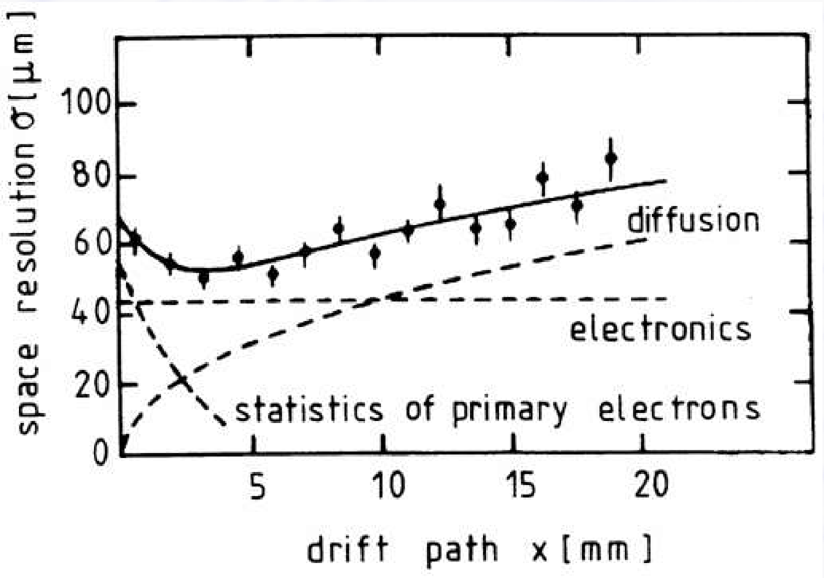
$$\sigma_{first} = \frac{\pi}{\sqrt{12 \ln(n_{el.})}} \sigma_x \approx 0.4 \cdot \sigma_x$$

Wire Chambers - Resolutions

- **Typical resolutions of drift chambers: 50...150 µm depends on the length of the drift path**
  - **primary ionization statistics: how many ion pairs, ionization flutuations**
    - dominates close to the wire
  - **diffusion: diffusion constant, drift length**
    - dominates for large drift length
  - **electronics: noise, shaping characteristics**
    - constant contribution, independent on drift length



very different drift lengths of electrons for tracks close to the wire, position of fastest electron very much dependent on ionization fluctuations

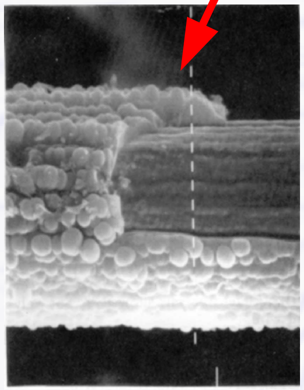


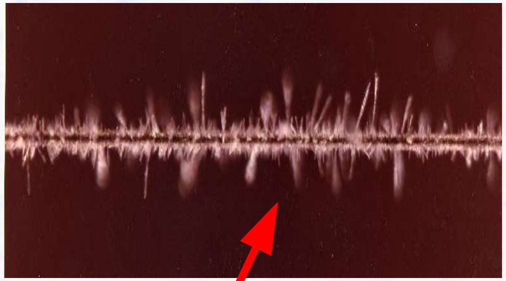
Wire Chambers – Ageing

more black magic...

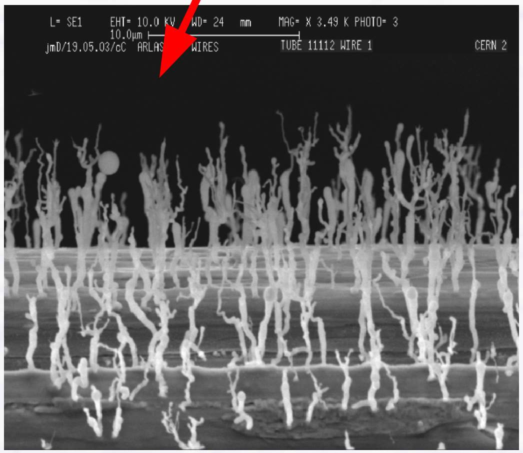
- **Wire Chambers don't work/live forever**
  - ➔ gas avalance region close to wire is region of plasma formation
    - ...and plasma chemistry not well understood in general
- **Avalance region**
  - dissociation of detector gas and pullutants
  - formation of highly active radicals
  - polymerization of organic quenchers
  - insulating deposits on anodes and cathodes

hard deposits, typically SiO_2 (quartz)

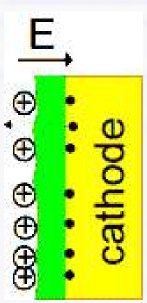




whiskers, typically carbon fibers



Anode: increase of wire diameter
reduced and variable E-field
variable gain and energy resolution



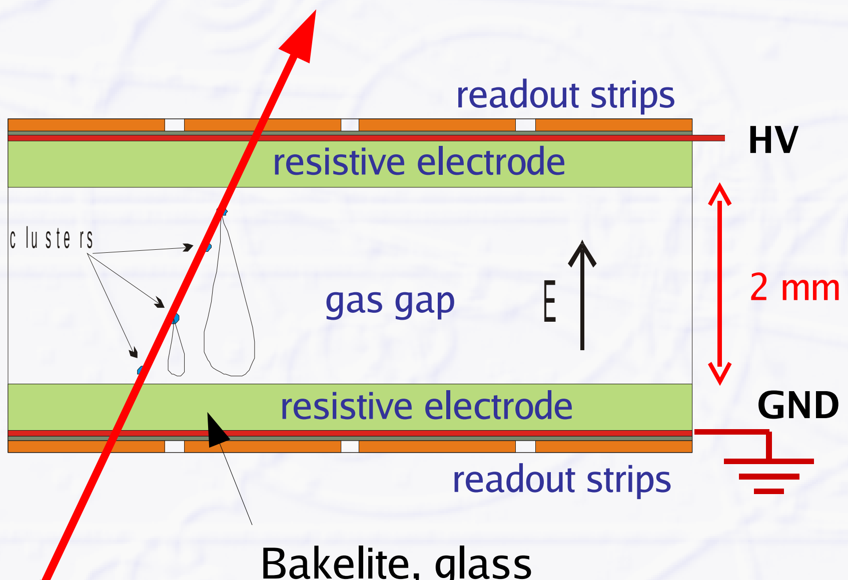
Cathode: ions on top of insulating layer cannot recombine
built-up of strong E-field across insulating layer
electron field emission and microdischarges

"Malter effect", first seen by L. Malter in 1936:
L. Malter; Phys. Rev. 50 (1936), 48

Conclusions of an ageing workshop many years ago:
CO_2 helps with water, and alcohol admixtures...

Resistive Plate Chambers (RPC)

- **There are also gaseous detectors without wires**
  - two resistive plates (~10^9 Ω cm) with a small gas gap (2 mm) and large high voltage (12 kV) on outside electrodes
  - strong E-field: operation in “streamer mode”
    - gas avalance already starting in gas gap (no wires involved)
    - developing of “streamers” (blob with lots of charge, almost like a spark)
    - signal on external read-out strips via influence (segmented for position resolution)
    - streamer/discharge is “self-quenching”: stops when near-by resistive electrodes are locally discharged (E-field breaks down)



Advantages: simple device, good to cover large areas, VERY fast!!!

→ used as trigger devices in LHC experiments, time resolution ~ 50 – 100 ps

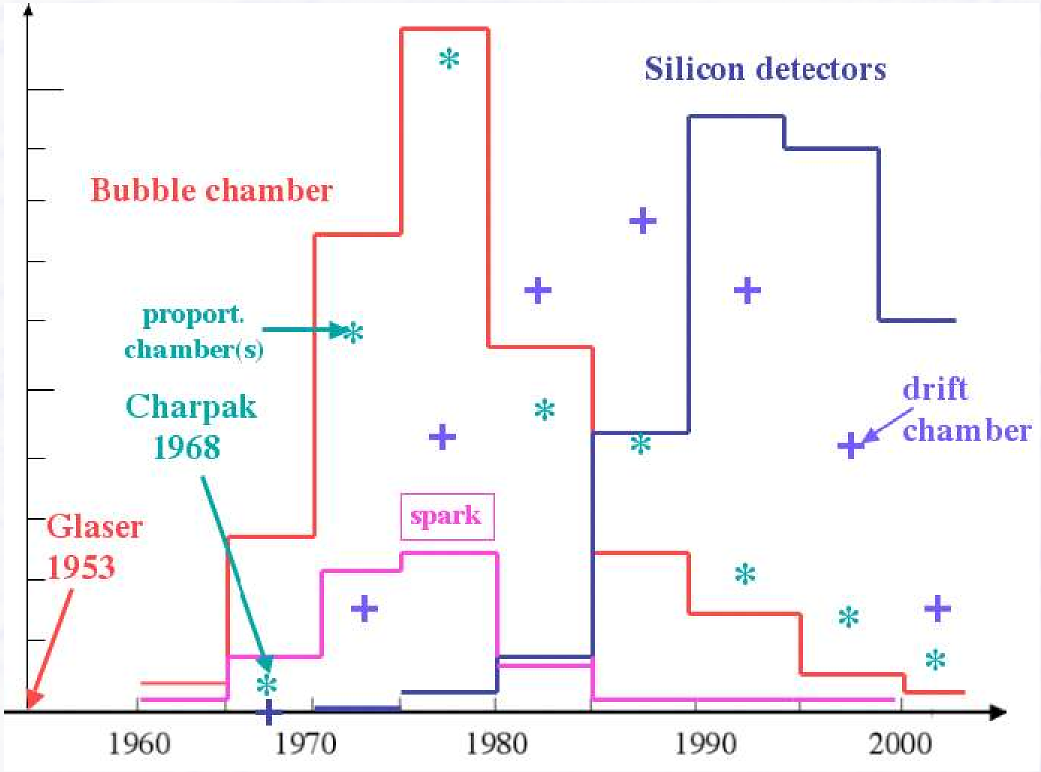
Disadvantages: Choice of resistive material + surface quality crucial, affects “dark” trigger rate

Gas Detectors in LHC Experiments

- Mainly used in Muon Systems (ALICE, ATLAS, CMS, LHCb)
  - precise muon tracking (drift tubes) and triggering (RPC)
- Also in Inner Tracking system (ALICE, ATLAS, LHCb, TOTEM)
  - mainly straw tubes = small, light weighted tubes
  - but not the innermost detector layer
    - domain of semi conductor (silicon) detectors
- Specific LHC challenges (for gas detector systems)
  - high track rate (25 ns) and density (~1000 tracks per bunch crossing)
    - need short drift times (avoid integrating over too many bunch crossings) + high granularity = fast gases, small sized detectors
    - need "ageing-free" gases/detectors
      - lots of effort spent over years in this field
      - extensive irradiations with Gamma irradiation source, lab studies with X-ray sources etc.

Detector History

- **Cloud Chambers dominating until the 1950s**
  - 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 (Big European Bubble Chamber), now in front on the CERN Microcosm exhibition
- **Wire Chambers (MWPCs and drift chambers) started to dominate since 1980s**
- **Since early 1990s solid state detectors are in use**
  - started as small sized vertex detectors
  - now ~200 m^2 silicon surface in CMS tracker



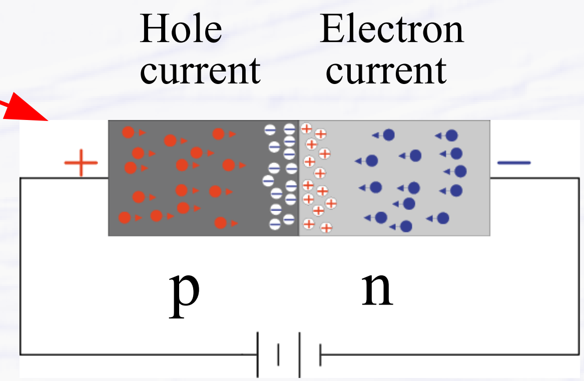
Solid State Tracking Detectors

- **Basic element of a solid state (silicon) detector is... a diode**
  - **p-type and n-type doped silicon material is put together**

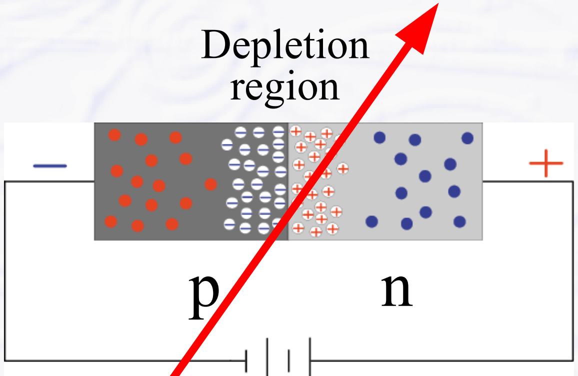
more holes

more electrons

Current flow through diode if connects like this



  - **for use as particle detector diode needs to be connected in opposite way**



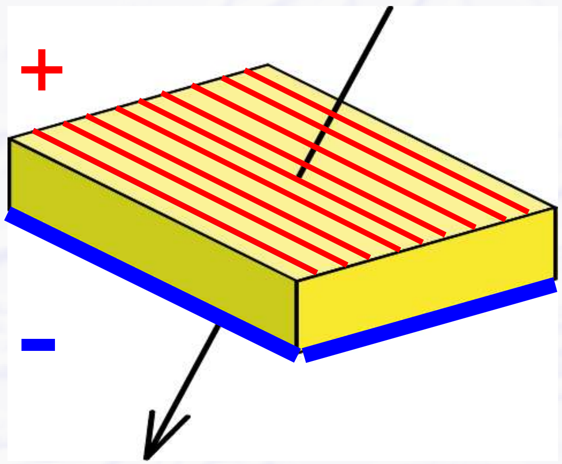
- **around junction of p- and n-type material depletion region is created**
  - **zone free of charge carriers**
    - **no holes, no electrons**
    - **thickness of depletion region depends on voltage, doping concentration**

charged particle can create new electron/hole pairs in depletion area sufficient to create a signal

typically 20'000 – 30'000 electron/hole pairs in 300 μm thick material

Silicon Tracking Detectors

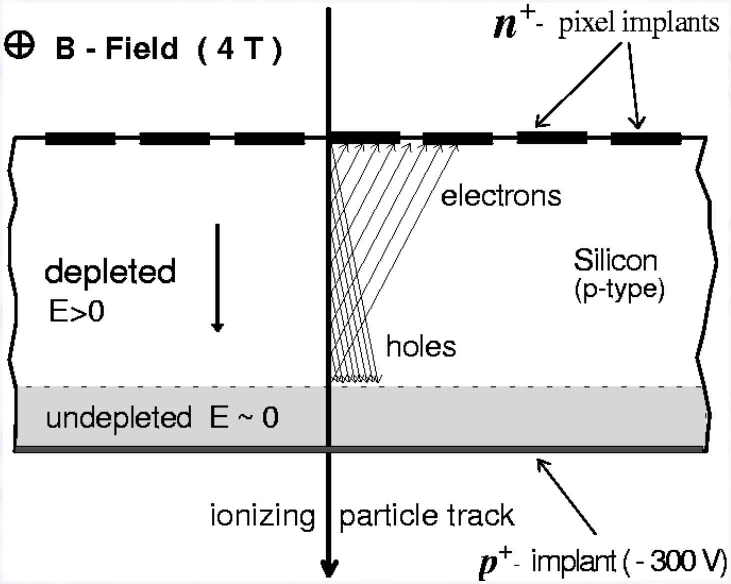
- Now take a large Si crystal, e.g. 10 x 10 cm², 300 μm thick



make bottom layer p-type

and subdivide the top n-type layer into **many strips with small spacing**

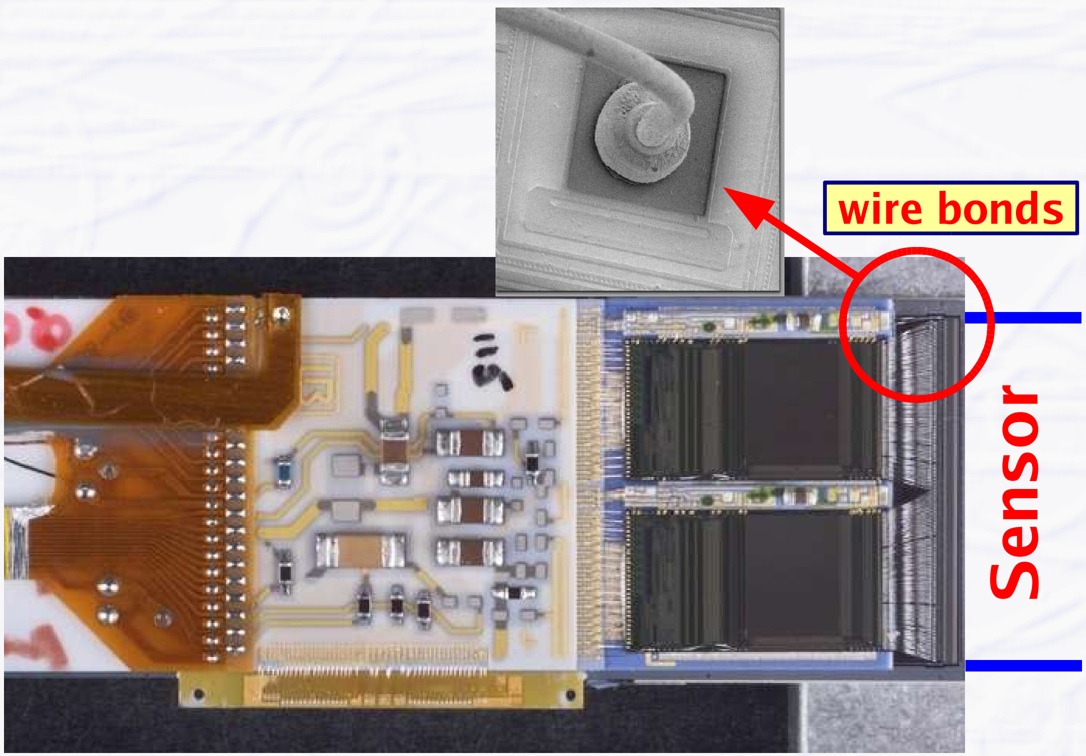
→ many diodes next to each other (like MWPC at wire chambers) with **position information**



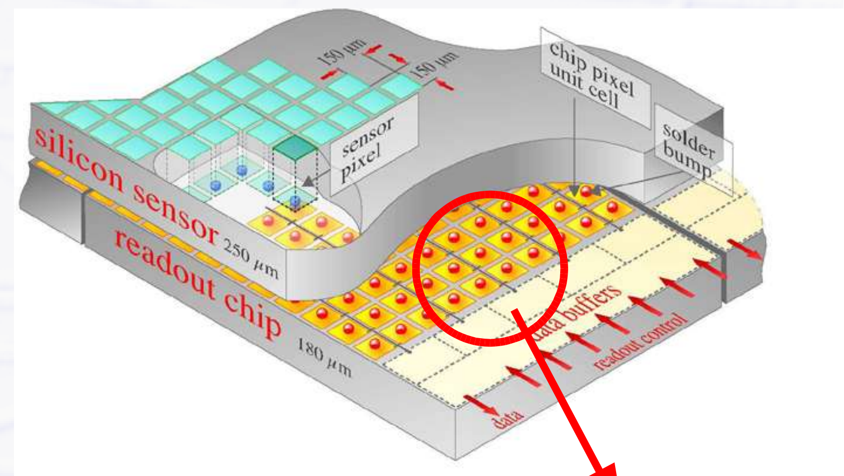
- Advantage compared to wire/gas detectors
  - strip density (pitch) can be rather high (e.g. ~20 μm)
    - high position accuracy
    - but also many electronics channels needed

Si-Detector Electronics and Si-Pixels

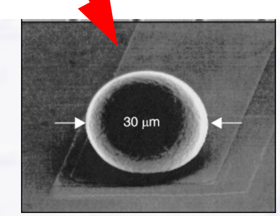
- **Silicon detectors have a laaaarge number of electronics channels, ~10^7 each for ATLAS and CMS Si trackers**
  - **requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)**
- ➙ **electronics is directly connected to the sensor (the “multi-diode”) via wire bonds**



Si-strip detectors provide only 1 coordinate,
Pixel detectors are 2D detectors

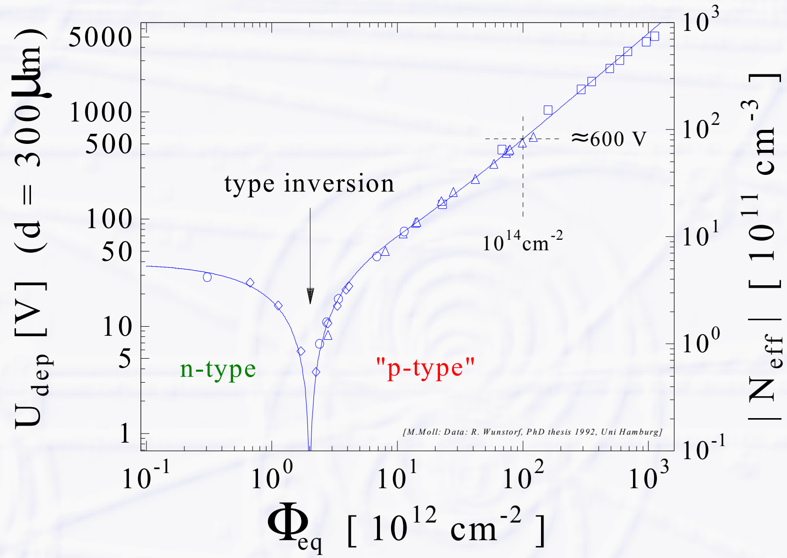


Pixel detector need “bump” bonding and have even more channels, ~10^8 - 10^9



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



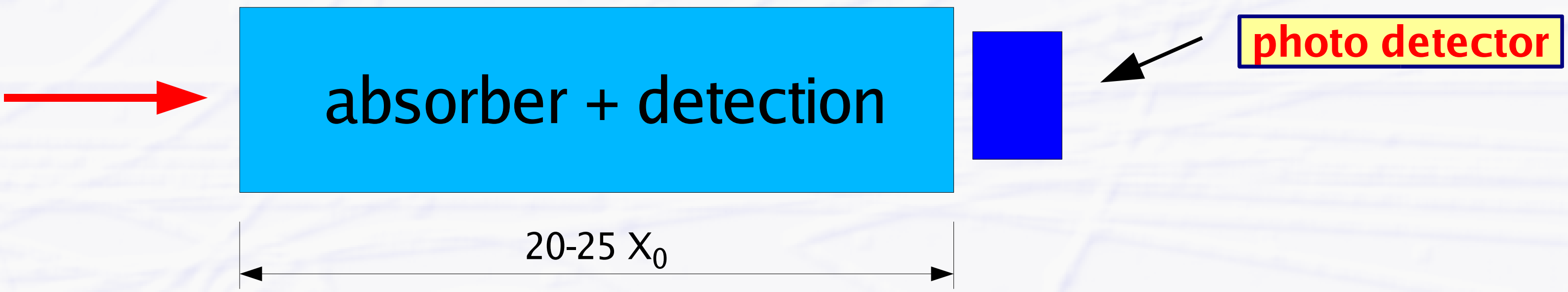
"Type inversion": n-type material changes to p-type material after a certain accumulated radiation dose

Calorimeters

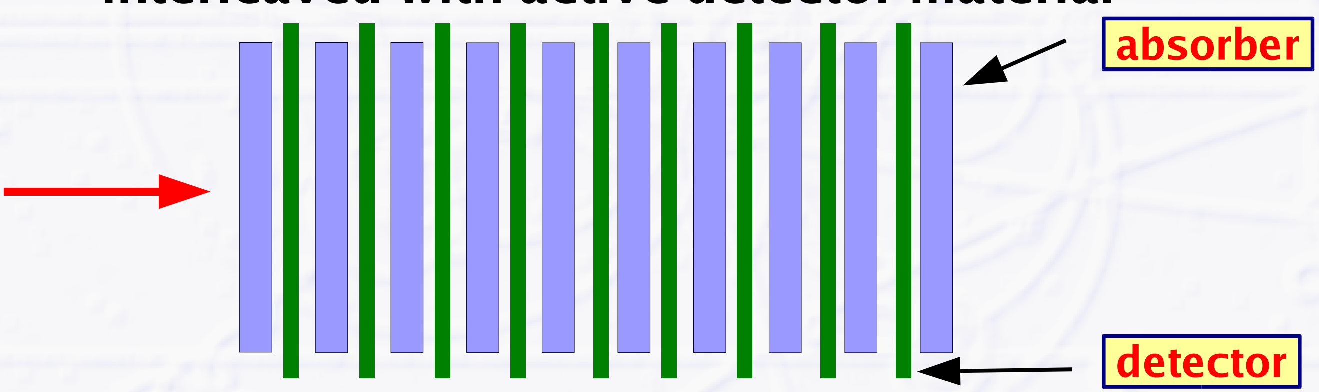
- Homogeneous and Sampling Calorimeters
- Electromagnetic and Hadronic Calorimeters
- Photon Detectors

Calorimeter Concepts

- **Homogeneous calorimeters**
  - **absorber material (generation of the shower) = detector material**
    - **typically an electromagnetic shower is created in an optical transparent absorber, photons created in the shower are collected and detected with some photo detector**

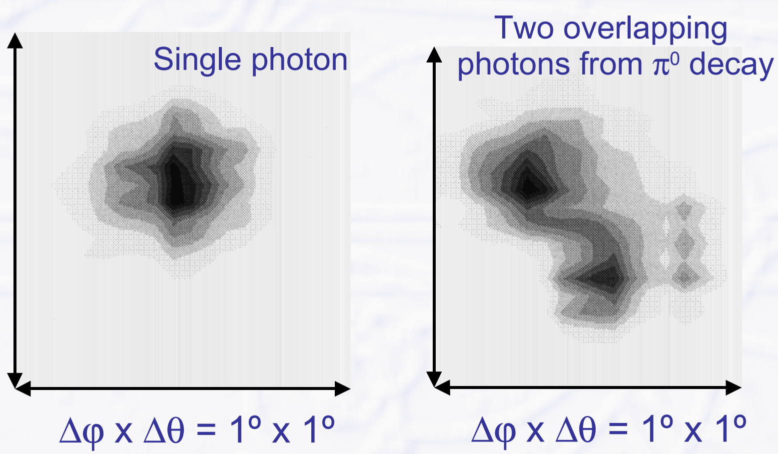


- **Sampling calorimeters**
  - **passive (heavy) absorber material (iron, copper, lead, tungsten, uranium) interleaved with active detector material**



Homogeneous Calorimeters

- **Clear advantage: good energy resolution**
  - **the entire shower is kept in active detector material**
    - **no shower particle is lost in passive absorber**
- **Disadvantages**
  - **limited granularity, no information on shower shape in longitudinal direction (along particle flight direction)**
    - **position information is useful to resolve near-by energy clusters, e.g. single photons versus two photons from π^0 decay**



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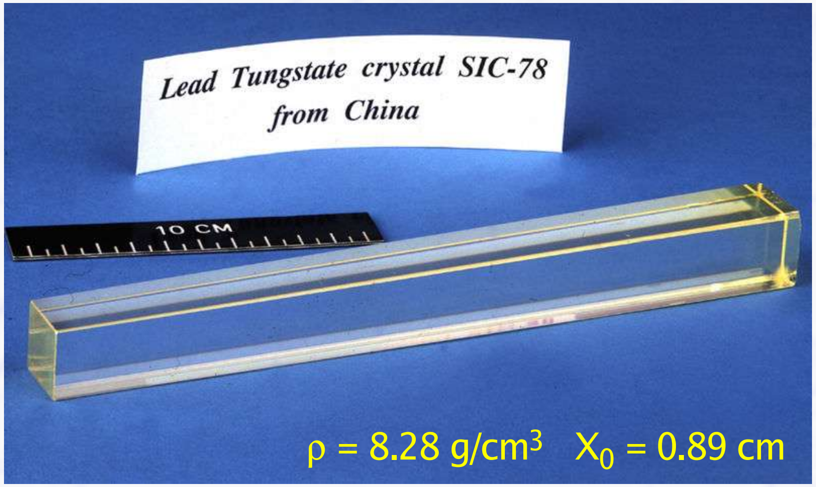
dense, transparent materials needed with short radiation length and high light yield

CMS $PbWO_4$ crystal

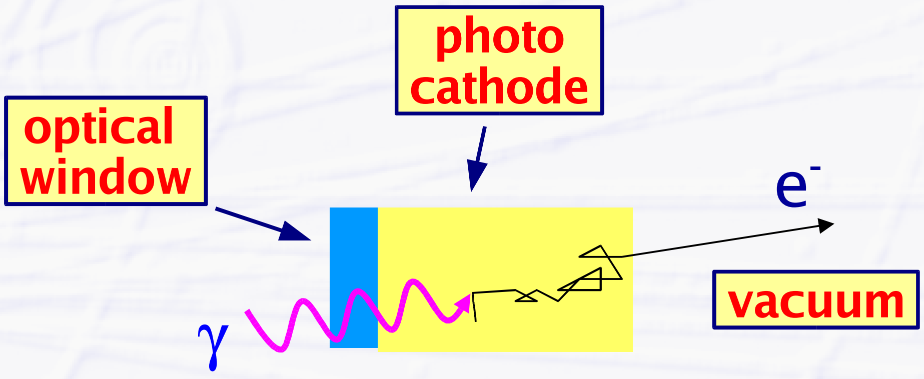


Photon Detectors

- We need to convert photons into an electronic signal
  - use photo effect
- Requirements
  - sometimes only a few photons available (Čerenkov radiation)
    - need high quantum efficiency (high efficiency to convert 1 $\gamma \rightarrow$ 1 e-)
  - even with high(est) photon conversion efficiency
    - signal from a single electron after conversion is not sufficient
    - need multiplication mechanism to get signal well above noise level of electronics
      - typical noise level: O(100) electrons
- Main types
  - vaccum-based (classical Photo Multiplier Tube PMT)
  - gas-based
  - solid-state (solid state photo diodes)
  - hybrid (mixture of above types)

Photo Cathodes

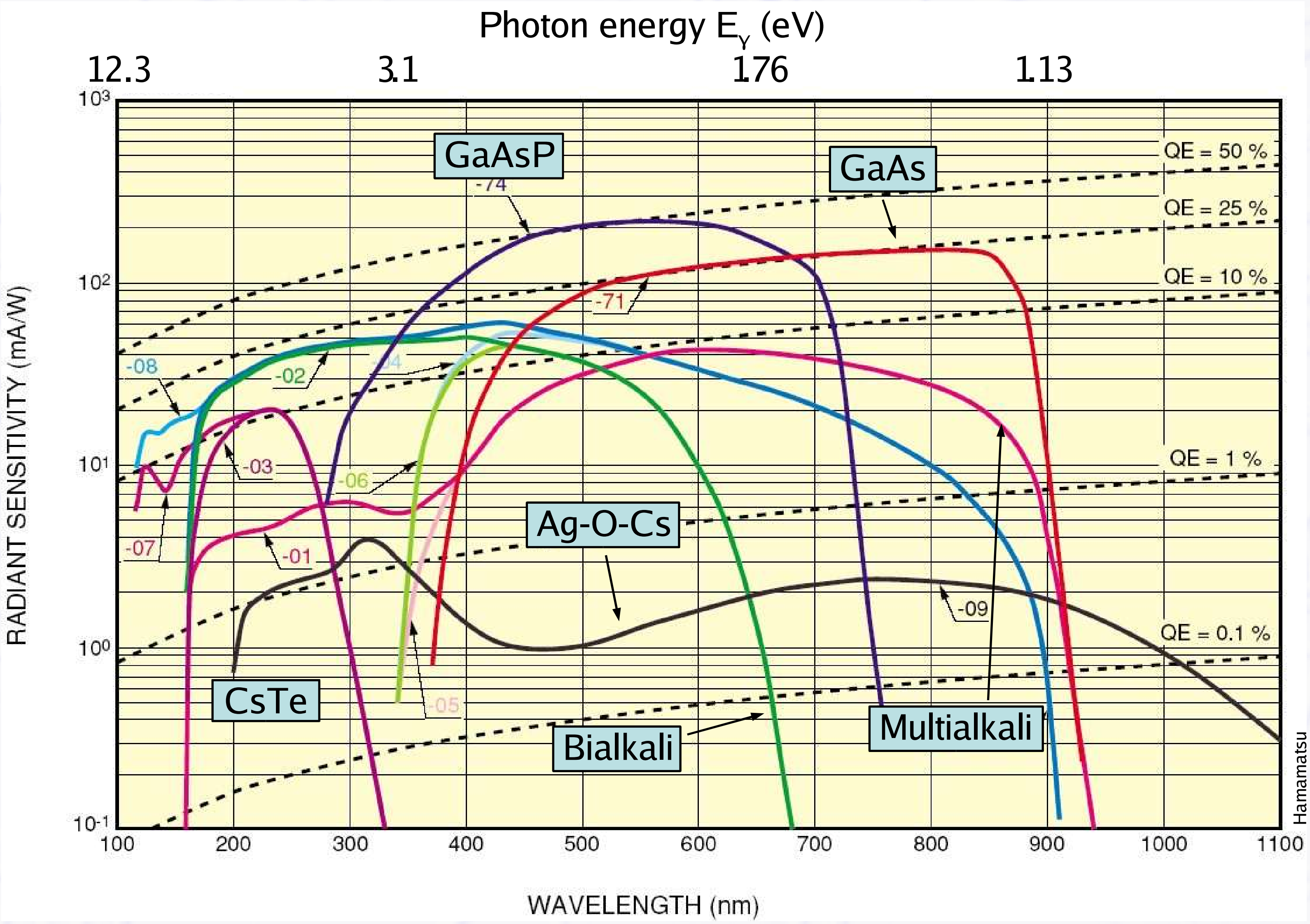
- 3-step process of photon to electron conversion
  - photon absorption
    - photon is absorbed in photo cathode
      + creates electron with some energy
      by photo effect
  - electron diffusion
    - electron moves through photo cathode
      material, affected by multiple scattering
      with some energy loss
  - electron emission
    - electron reaches surface with sufficient
      energy (work function) to escape into vacuum



- Typical losses
  - photon already reflected/absorbed at/in optical window
  - photon passes through photo cathode layer without creating an electron
    - photo cathode layer too thin
  - electron is loosing too much energy before reaching surface
    - photo cathode layer too thick or work function too high

Quantum Efficiencies

- **Typical photo cathode materials**
  - **alkali metals (have low work function)**



Energy Resolution

- **Number of particles in shower should be proportional to energy of initial particle** $N_{\text{track}} = \frac{E}{E_c}$
  - error of energy measurement mainly determined by fluctuations in the number of tracks
    $$\sigma(N_{\text{track}}) = \sqrt{N_{\text{track}}}$$
  - so the relative energy measurement error is $\frac{\sigma(E)}{E} \propto \frac{1}{E}$
- **This is just the statistical (stochastic) measurement error**
  - more contributions come from detector inhomogenities and noise
  - in general

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

convolution

stochastic term

constant term: inhomogenities, non-linearities

noise term: electronics noise

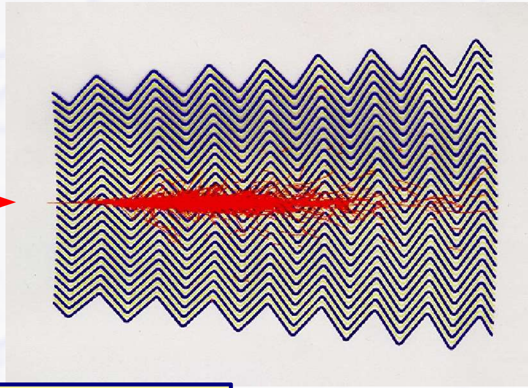
this relationship is valid both for homogeneous + sampling calorimeters and for both electromagnetic and hadronic calorimeters

Sampling Calorimeters

- **Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible**
  - gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)
- **ATLAS is using LAr with "acordeon" shaped steel absorbers**
  - LAr is ionized by charged shower particles
  - Charge collected on pads
    - ionization chamber, no "gas" amplification
    - pads can be formed as needed → high granularity
  - Energy resolution (test beam)

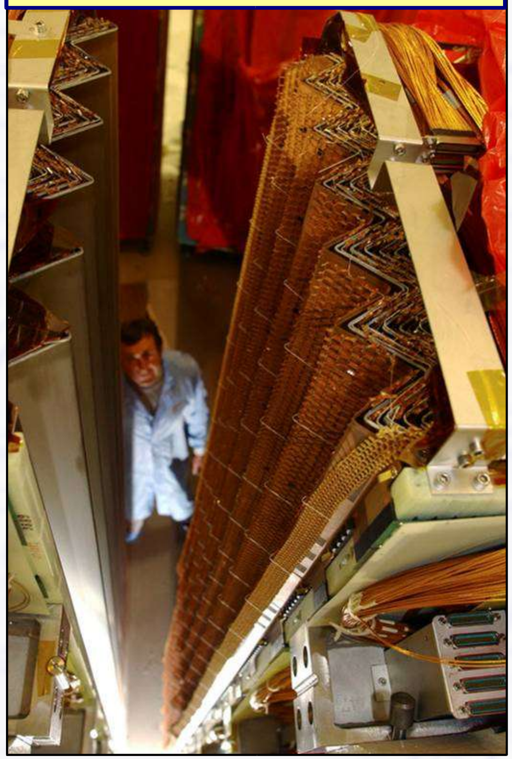
$$\frac{\sigma(E)}{E} = \frac{9.24\,\%}{\sqrt{E}} \oplus \frac{0.23\,\%}{E}$$

  - acordeon structure helps to avoid dead zones (cables etc.)



simulated shower

ATLAS LAr calorimeter

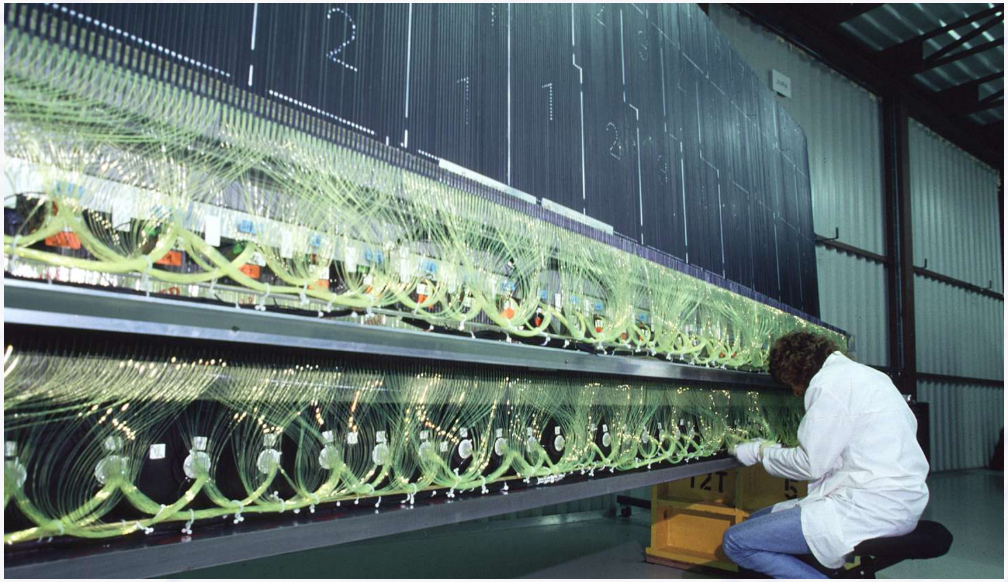


Hadron Calorimeters

- **Energy resolution much worse than for electromagnetic calorimeters**
  - **larger fluctuations in hadronic shower**
  - **usually only a few nuclear interactions length deep (5 – 6 λ_I)**

CMS $$\frac{\sigma(E)}{E} = \frac{65\%}{\sqrt{E}} \oplus \frac{5\%}{E}$$

- **Both ATLAS and CMS use scintillators as detector material**
  - ➠ **need many optical fibers to transport light from scintillators to photo detectors**

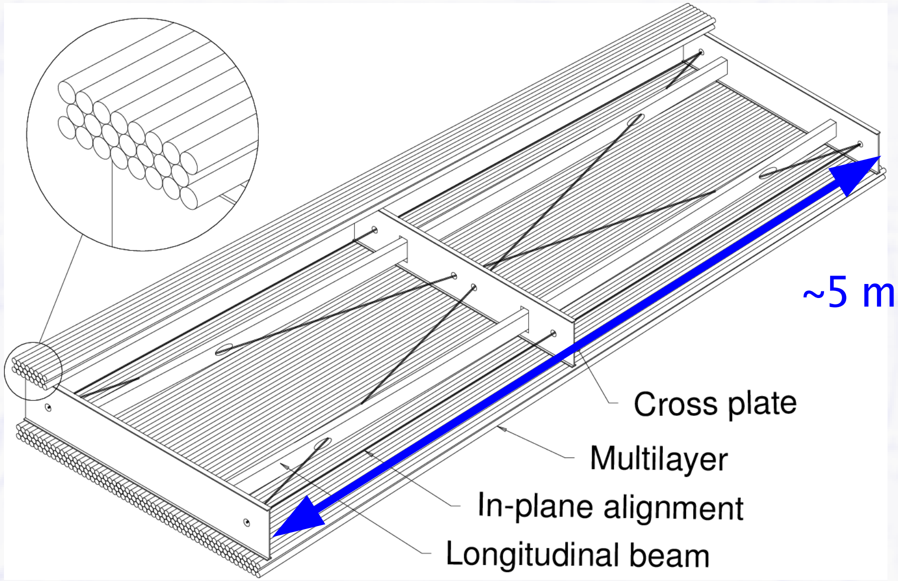


Muon Detectors

- Muon detectors are tracking detectors (wire chambers)
  - they form the outer shell of the (LHC) detectors
  - they are not only sensitive to muons (but to all charged particles)!
  - just by "definition": if a particle has reached the muon detector it's considered to be a muon
    - all other particles should have been absorbed in the calorimeters
- Challenge for muon detectors
  - large surface to cover (outer shell)
  - keep mechanical positioning stable over time
- ATLAS
  - 1200 chambers with 5500 m^2
  - also good knowledge of (inhomogeneous) magnetic field needed

ATLAS Muon Detector Elements

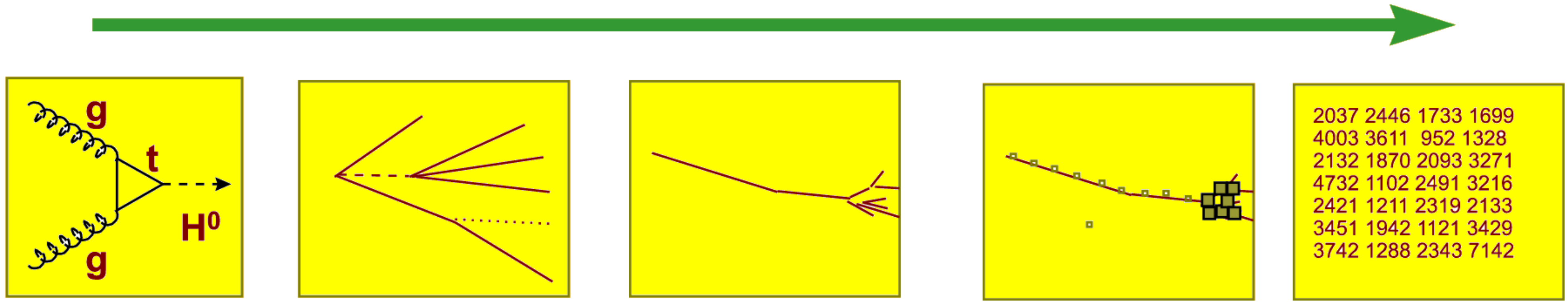
Aluminum tubes with central wire filled with 3 bar gas



Reconstruction and Detector Concepts

- From Physics to Raw Data and back
- Calibration, Alignment, Simulation
- ATLAS + CMS Detector Concepts
- Summary

From Physics to Raw Data



Basic physics

Fragmentation, Decay

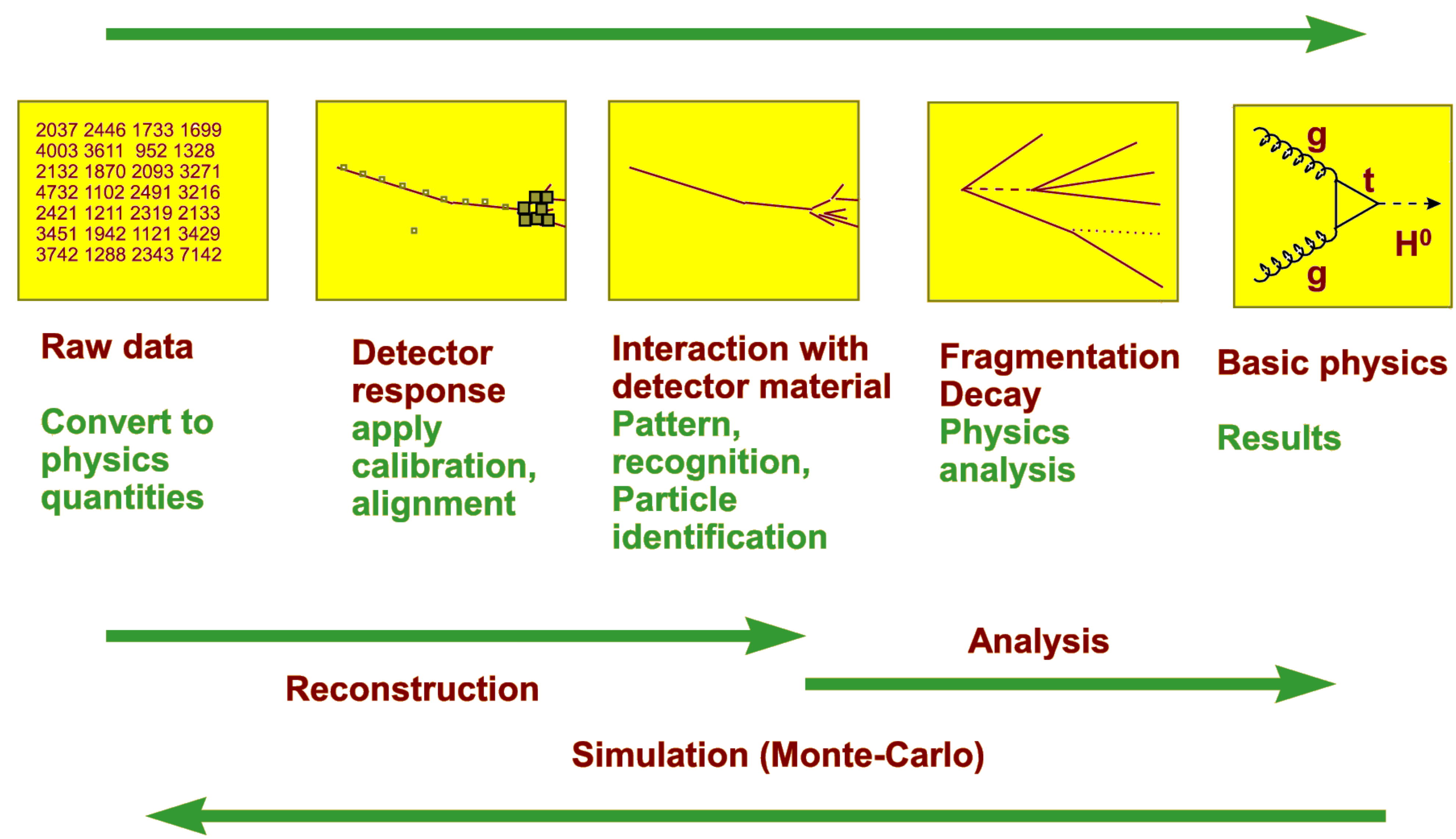
Interaction with detector material
Multiple scattering, interactions

Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data
Read-out addresses, ADC, TDC values, Bit patterns

- **Actually recorded are raw data with ~400 MB/s for ATLAS/CMS**
  - **mainly electronics numbers**
    - e.g. number of a detector element where the ADC (Analog-to-Digital converter) saw a signal with x counts...

From Raw Data To Physics



- **We need to go from raw data back to physics**
  - reconstruction + analysis of the event(s)

Calibration

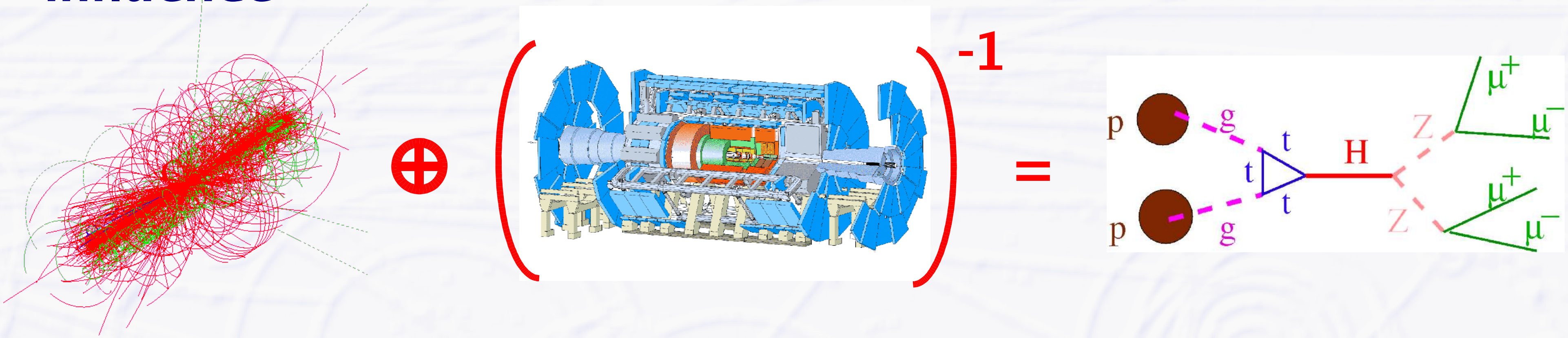
- E.g. need to know
  - how many ADC counts in a certain region of the calorimeter are equivalent to a 100 GeV electron (scaling factor)?
  - how linear is the calorimeter over the full energy range? scaling factor constant?
  - how different are the scaling factors in the various calorimeter regions?
- Possible ways to get this information (calibration data)
  - test beam: put detector in electron beam with know energy and check all regions before installing
    - not possible for all detector elements, time constraints, availability
  - use (known) electronic test pulses, light sources etc.
  - calibrate with LHC data, e.g. use $Z^0 \rightarrow e^+e^-$ decays
    - try to identify electrons, measure electron energies, reconstruct invariant mass
    - if reconstructed mass $\neq Z^0$ mass $\rightarrow$ correct scaling factors
    - requires lots of statistics (can take ~year(s?) to collect sufficient calibration data)

Alignment

- **Silicon detectors have a very good point resolution, ~10 µm**
  - but where is this point exactly in space, w.r.t. the global detector coordinate system?
  - resolution ≠ absolute accuracy
- **Point is usually defined by strip number or pixel number**
  - = within the local Si detector frame (10 x 10 cm^2 scale)
  - limited mechanical positioning of one Si detector element to each other
    - shifts and rotation of the elements, bowing (non flatness) etc.
    - need to know all positions of the detector elements
- **Possible alignment strategies**
  - can measure positions in the lab before installation (survey)
    - stability after installation?
  - use alignment system (e.g. laser tracks, piezo) to measure positions
  - align with LHC tracks, e.g. minimize deviations from track in χ^2 fit

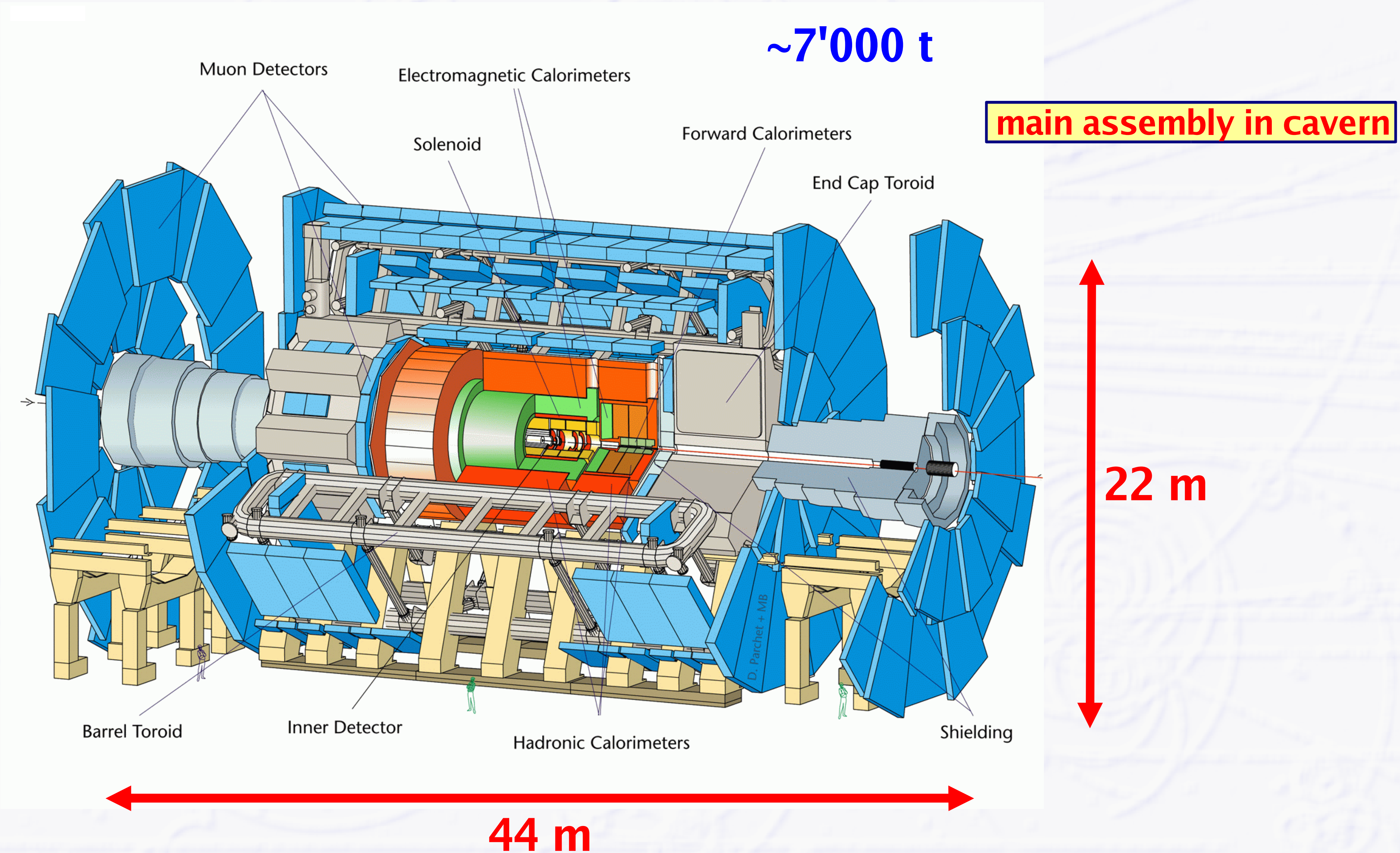
Simulation (Monte Carlo)

- **Even with best calibration + alignment**
  - some detector influence, e.g. efficiency for track reconstruction etc. will not be known well enough from data
- **Use detector simulation (Monte Carlo) to "unfold" detector influence**



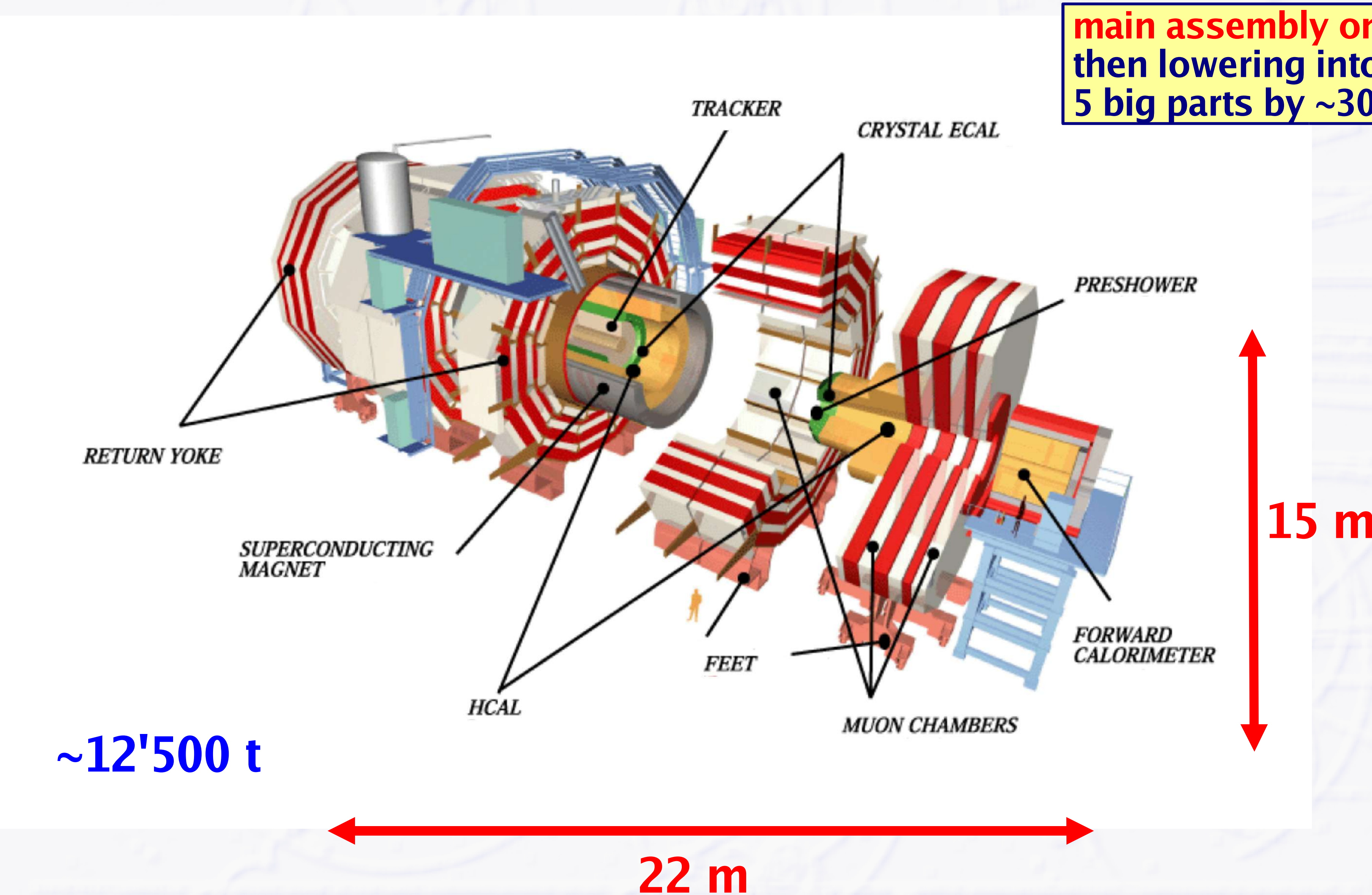
- **Simulation contains full detector description**
  - geometry, detector volumes, detector response (noise etc.)
  - physics interactions with matter and tracking particles through detector volumes (GEANT3/GEANT4 package)
  - also needed for detector design studies before detector actually built

ATLAS (A Toroidal LHC ApparatuS)



CMS (Compact Muon Spectrometer)

main assembly on surface, then lowering into cavern in 5 big parts by ~3000 t crane



ATLAS/CMS

- **The two large LHC detectors have somewhat different concepts**
  - **ATLAS**
    - **small inner tracker with moderate field (small 2 T solenoid)**
    - **sampling calorimeter with high granularity**
    - **air-core toroid system for good muon momentum measurement**

emphasis on granular calorimeter and good muon measurement

  - **CMS**
    - **large inner tracker with high B-field (large 4 T solenoid)**
    - **homogeneous crystal calorimeter with good energy resolution**

emphasis on good general tracking and good energy resolution

- **Physics and operational experience has to tell what might be the better concept for certain physics channels...**

ATLAS/CMS in detail

	ATLAS	CMS
Tracker or Inner Detector	Silicon pixels, Silicon strips, Transition Radiation Tracker, 2 T magnetic field (small solenoid)	Silicon pixels, Silicon strips, 4 T magnetic field (large solenoid)
Electromagnetic calorimeter	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate ($PbWO_4$) crystals both absorb and respond by scintillation
Hadronic calorimeter	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon detector	Large air-core toroid magnets with muon chamber form outer shell of the whole ATLAS	Muons measured already in the central field, further muon chambers inserted in the magnet return yoke

Summary I

- **Detector Challenge (following the physics case)**
  - **the LHC puts new demands on detector technology**
    - good momentum resolution up to TeV scale
    - high rate capabilities, fast, high granularity, radiation-hardness
  - **different magnet concepts at LHC experiments**
    - ATLAS: toroid system, CMS: “classical”solenoid
- **Tracking Detectors**
  - **momentum resolution has two main contributions**
    - error from multiple scattering, dominates at low momenta
      - requires thin detectors
    - error from point measurements, dominates at high momenta
      - good point resolution, large B-field and large track length helps (L^2)
  - **mainly two types of track detectors**
    - wire detectors (gas) since 1968s
      - point resolution limited by diffusion to ~50-150 μm
    - silicon detectors since early 1990s
      - very good point resolution, many electronics channels, “thick” compared to wire chambers

Summary II

- **Calorimeters**
  - two types of calorimeters
    - electro-magnetic (electrons and photons) and hadronic (hadrons)
    - dimension of calorimeters determined by radiation length (20-25 X_0) and nuclear interaction length (hadronic)
  - two basic concepts
    - homogeneous calorimeter, one type of material for both shower generation (absorption) and detection
    - sampling calorimeter, passive material for shower generation, active material for detection, less energy resolution but better granularity possible
- **Reconstruction and Detector Concepts**
  - recorded detector output is mainly electronics information
    - need detector calibration and alignment to reconstruct physics quantities
    - detector simulation (Monte Carlo) needed to unfold overall detector influence
  - ATLAS and CMS detector concepts have different focus
    - physics has to decide on the better concept

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