Karlsruher Institut für Technologie

Vorlesung:

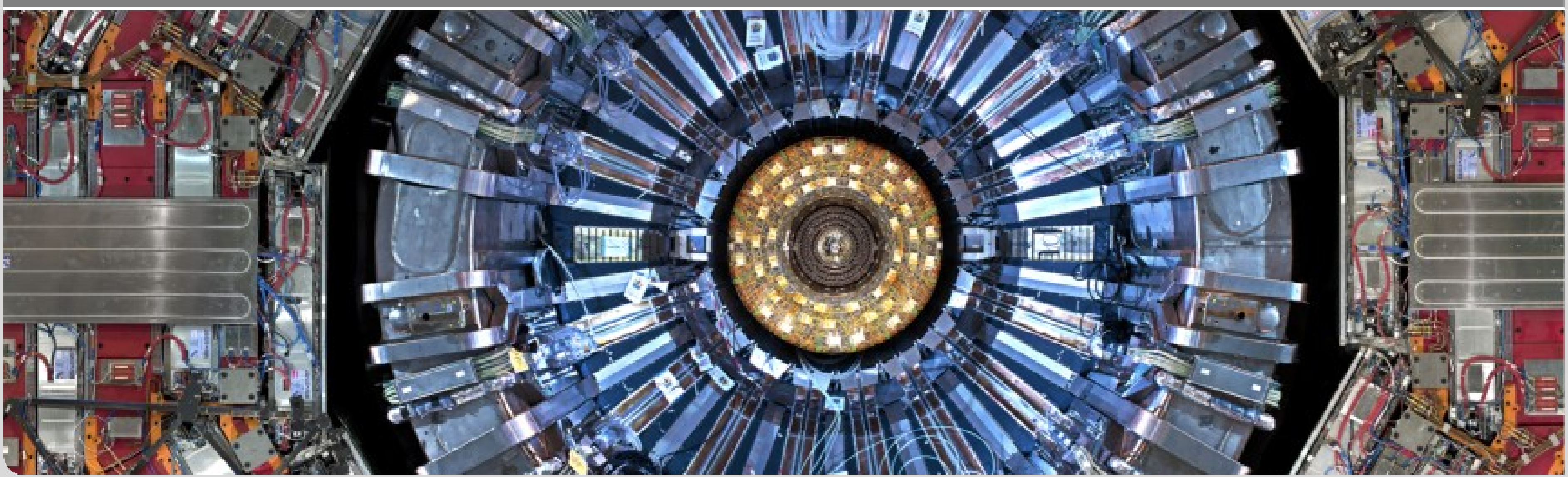
Teilchenphysik I (Particle Physics I)

Detector systems

Günter Quast

Fakultät für Physik
Institut für Experimentelle Kernphysik

WS 20/21

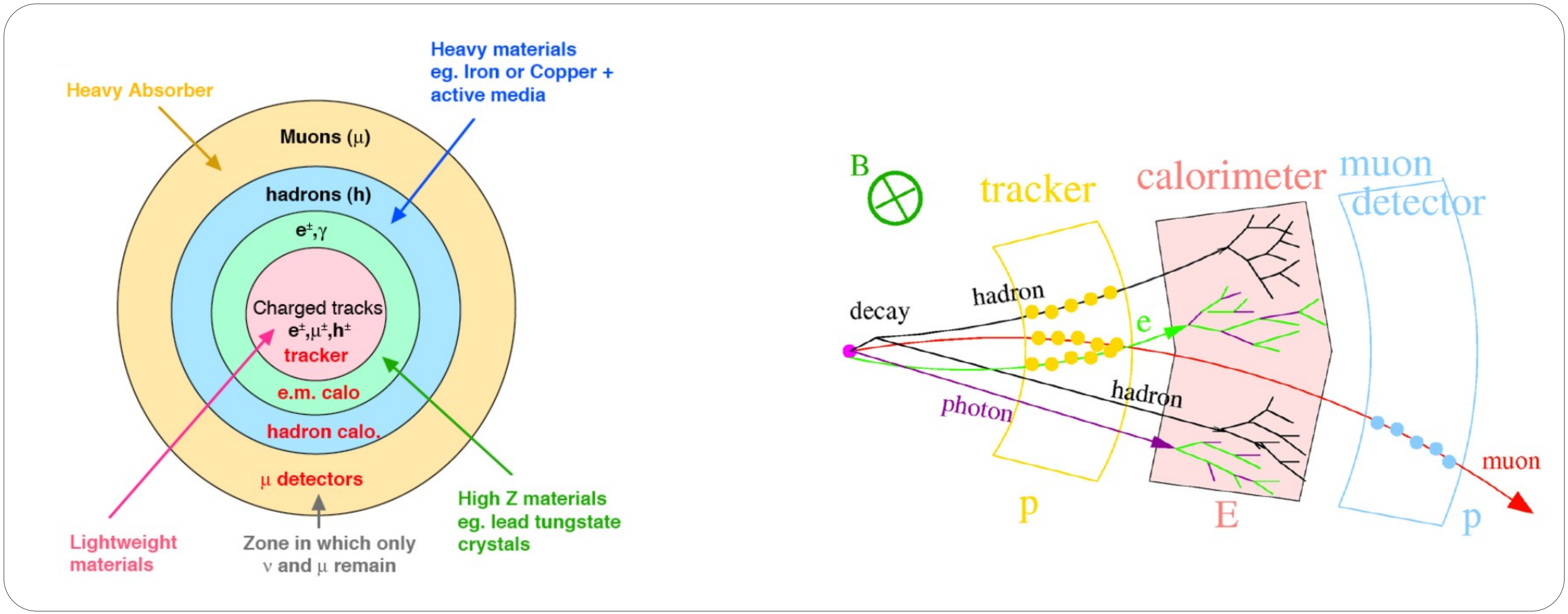


1. History
2. Basics principles
3. Detectors and Accelerators
    1. Interaction of particles with matter
    2. Simulation of particle interactions with Monte Carlo
    3. Detector Systems
    4. Accelerators

Introduction: Detector Systems

Combination of detector components needed
- to identify particles
- and precisely measure their momenta and / or energies

- vertex- and tracking detectors
- strong magnetic field for momentum measurement
- electromagnetic calorimeters
- hadron calorimeters
- myon detectors
- possibly spcial systems for particle identification



Identification and **precise measurement** of all (sufficiently) stable partilces:

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

Introduction: Detector Systems (2)

- **Detector system design is driven** by research goal and experimental environment and constraints
- Examples of experiments with particle beams
  - Multipurpose collider experiments, e. g. ATLAS and CMS at the LHC
  - Asymmetric collider experiments, e. g. LHCb, experiments at B factories, electron – proton collider HERA
  - Fixed-target experiments, e. g. neutrino experiments, early experiments
- Examples of experiments without accelerators
  - Multipurpose experiments in neutrino physics
  - Specialised experiments, e. g. to measure neutrino mass, search for dark matter

More details than can be given here:
Spezialvorlesung Detektoren

Principle of Particle Detection

relies on principles described in last lecture:

interaction of particles with matter leads to

- ionization → free charges in material
- photons (near visible spectrum) → light

Detection principle:

collect charge and/or light and transform to electrical signal

basic measured quantity: **"mV in detector cell"**

After **digitization** and **data collection** from all detector cells:

→ **data structure** consisting of **cell idenitifiers** and **measured signal heights**

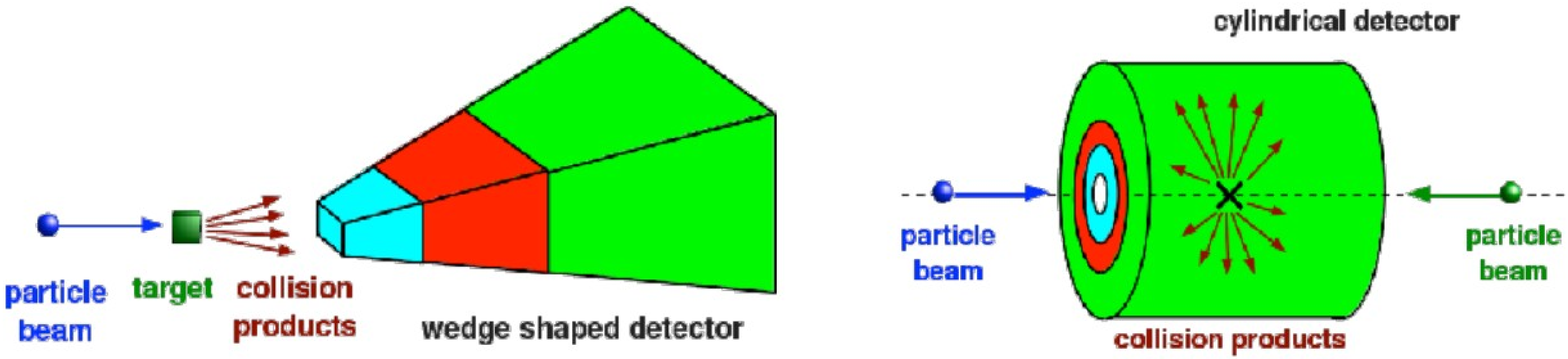
Data stucture is processed by complex software stacks to produce:

→ graphical displays: data visualisation

→ reconstructed physics objects (tracks,electrons, myons, photons, hadrons, jets …)

These high-level physics objects form the basis of the subsequent data analysis

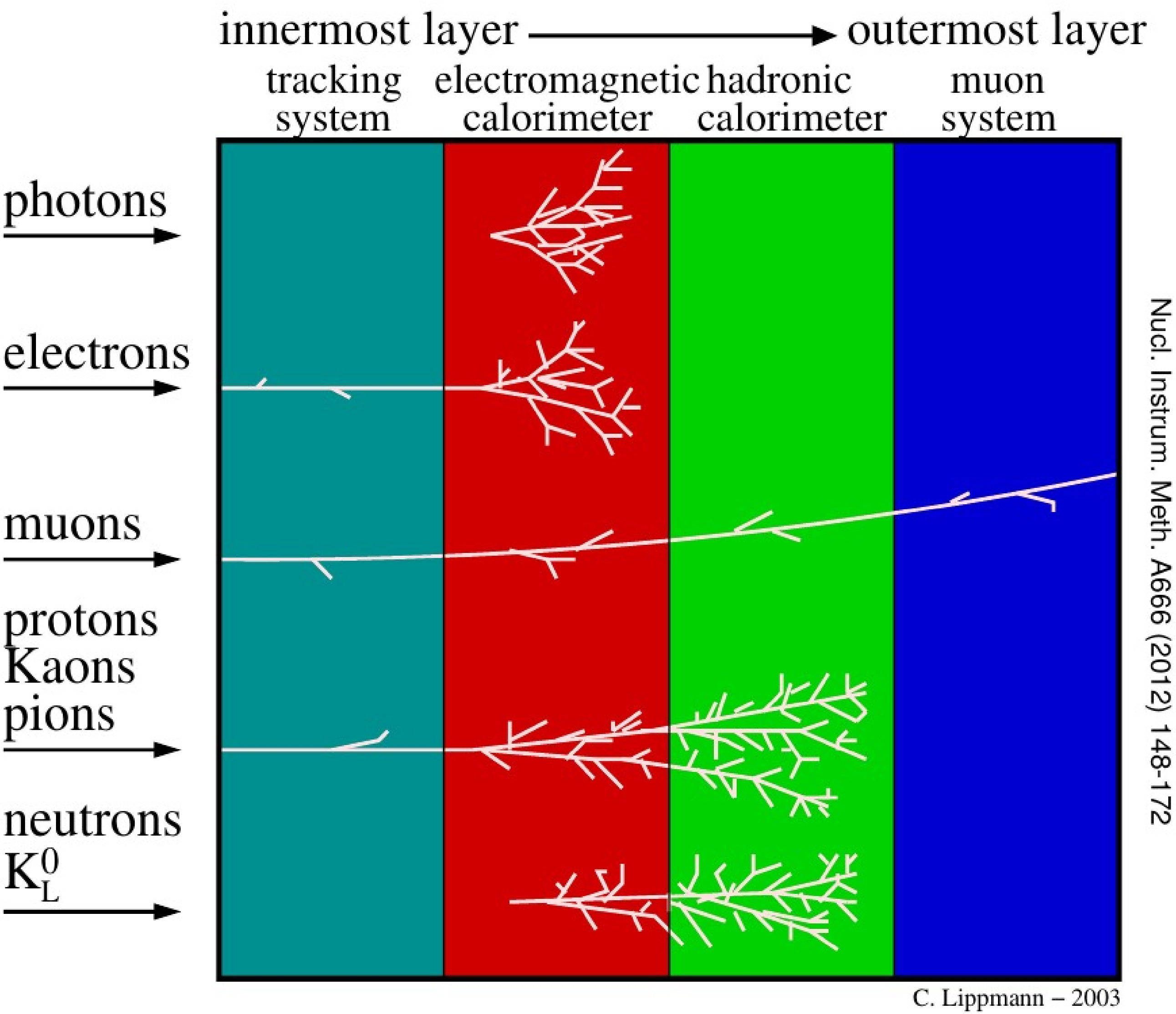
Fixed-Target and Collider Layout



H. Evans, copyright unknown

fixed target	***collider***
1 particle beam hits fixed target	2 particle beams collide
collision products in forward direction	collision products in all directions
"forward spectrometer" detector	cylindersymmetric "4π" detector

Particle detection and identification



momentum, direction, (type)

energy, (direction, type)

type, momentum, direction

Concrete example: the CMS detector

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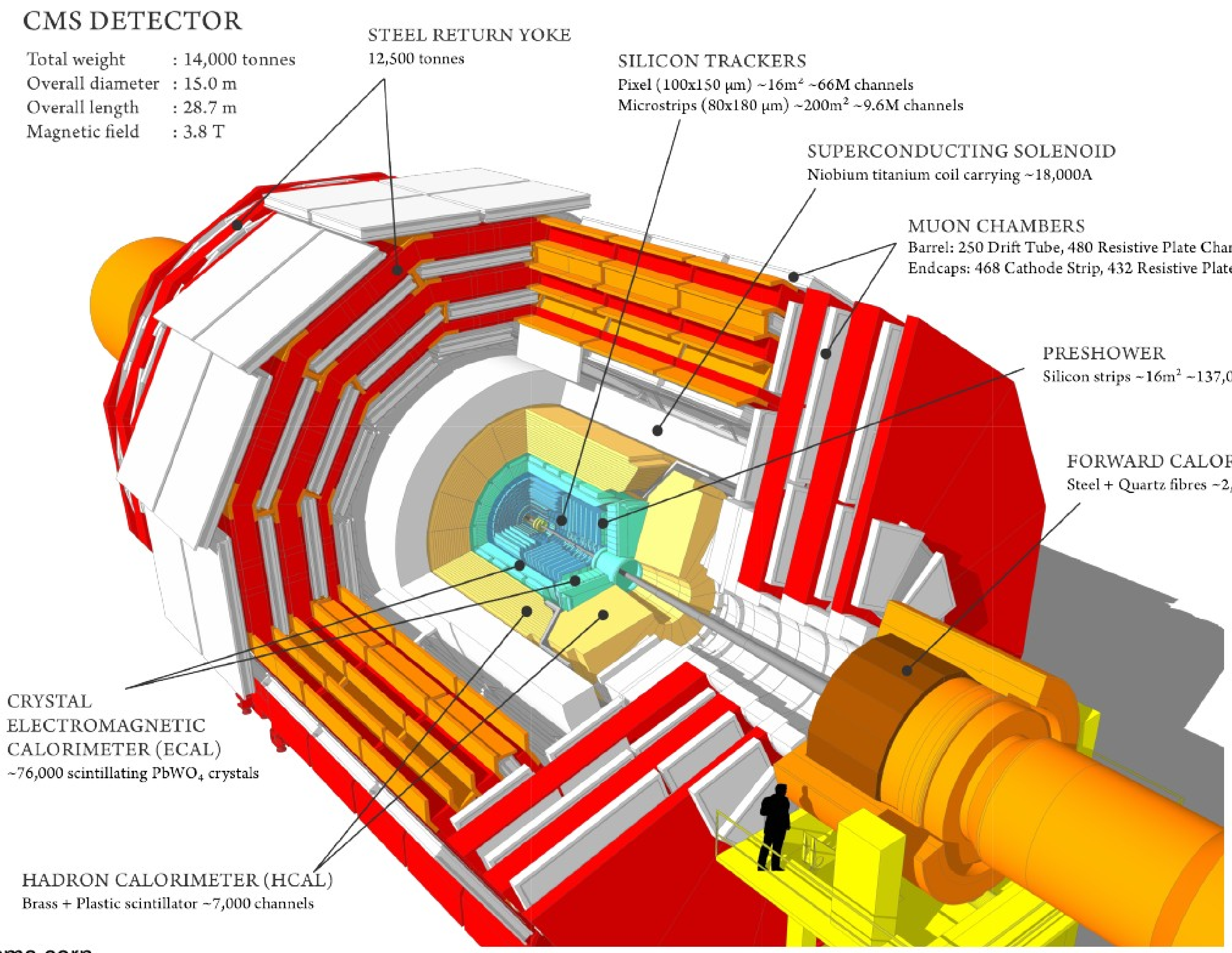
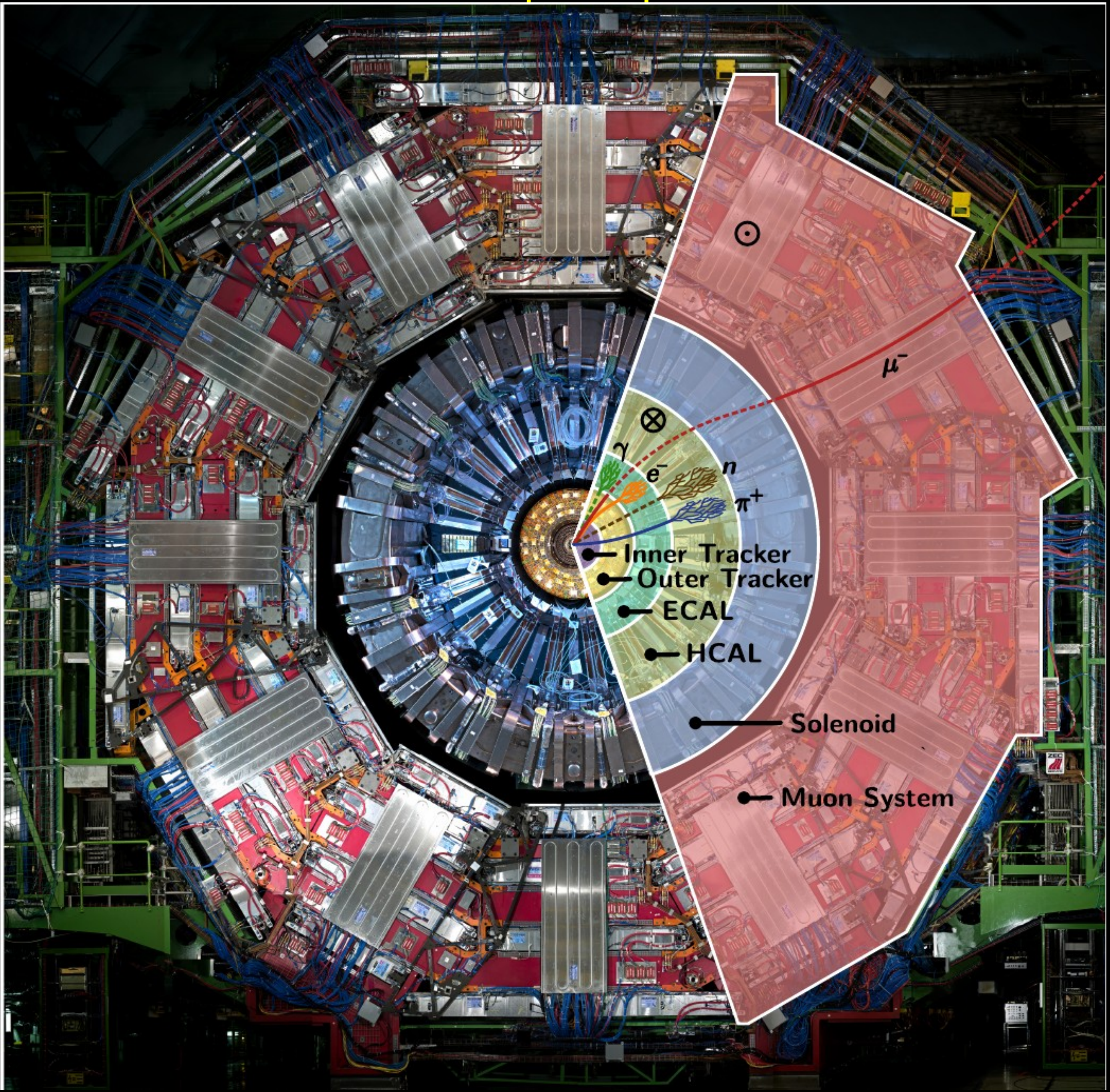
Multipurpose experiment



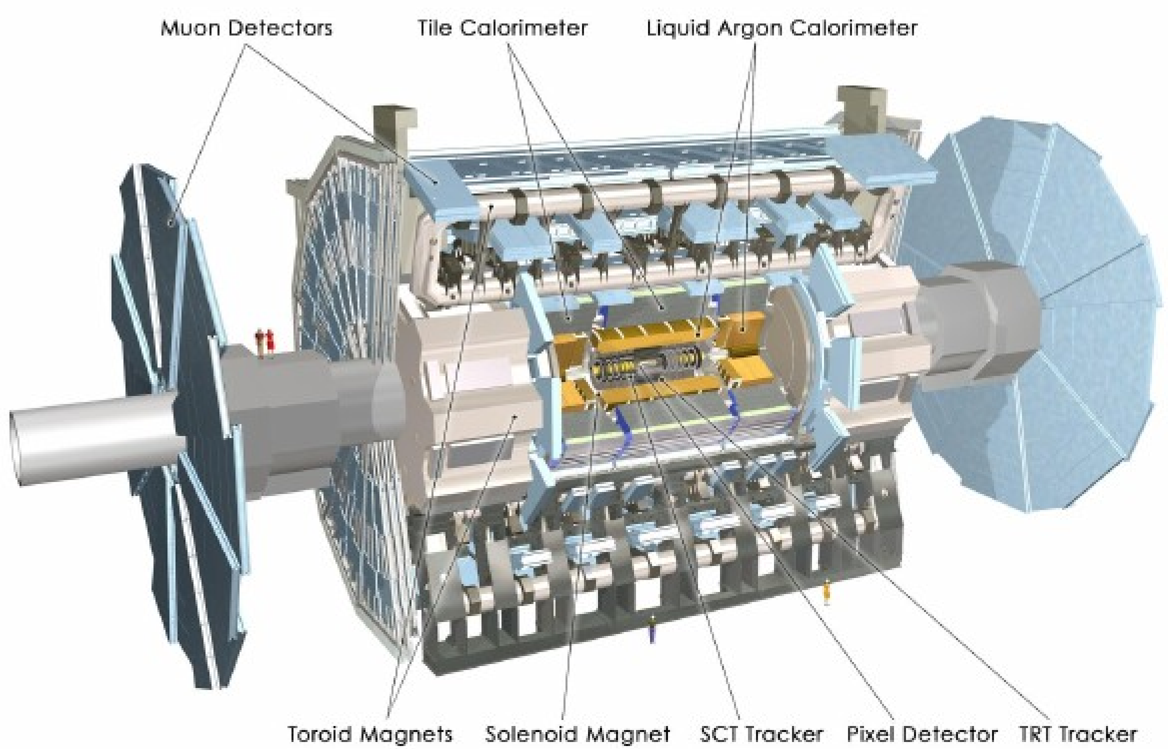
cms.cern

Funktionsprinzip eines Detektors: CMS



Quelle: Dissertation
Joram Berger,
Karlsruhe, Juli 2014

concrete example 2: the ATLAS Detector



same goals as CMS with (slightly) different approach:

- solenoid surrounding tracker
- toroidal magnet systems for myon measurements

TABLE 2 Main design parameters of the ATLAS and CMS detectors

Parameter	ATLAS	CMS
Total weight (tons)	7000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	4
Solid angle for precision measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (million Swiss francs)	550	550

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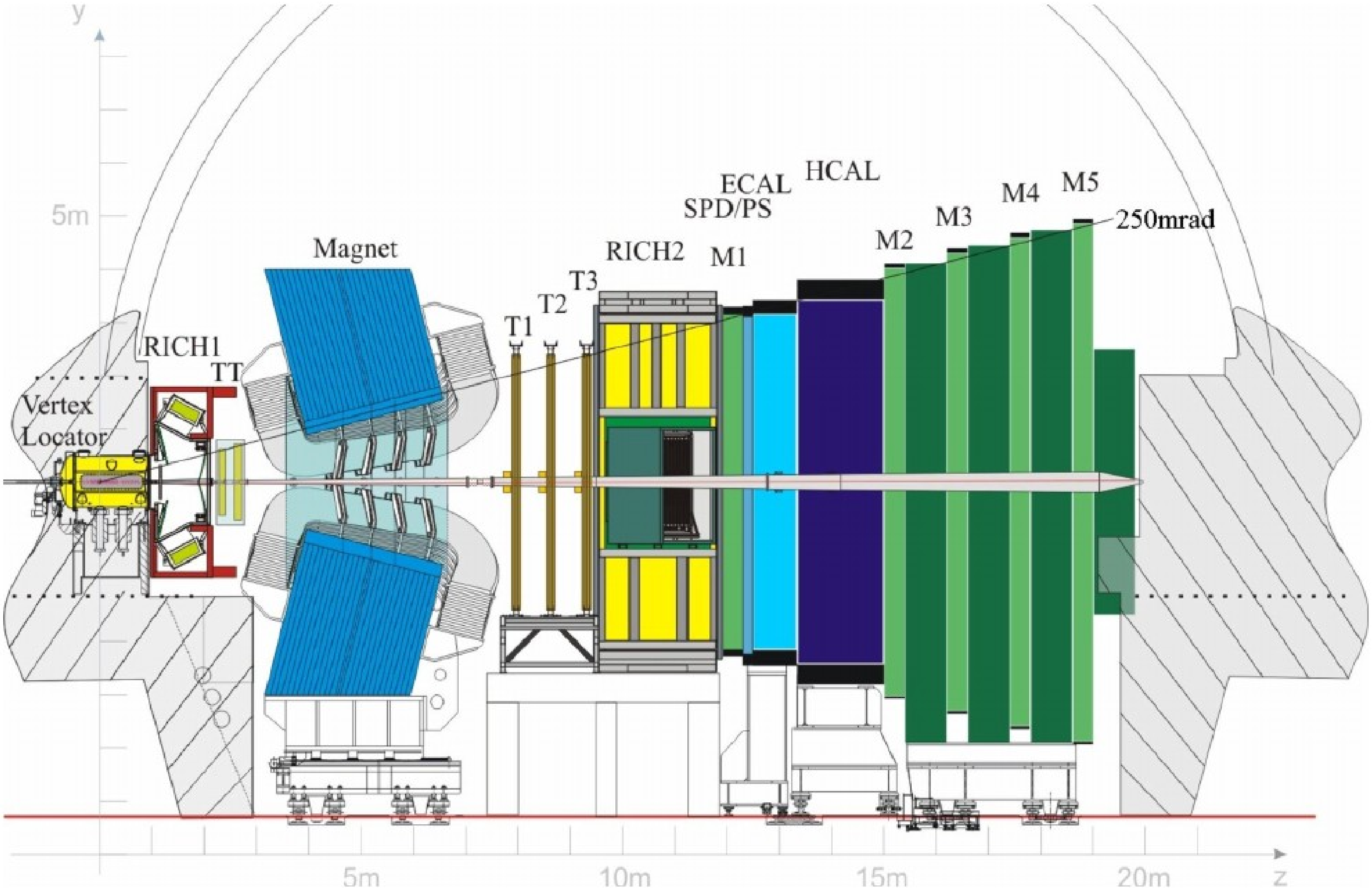
ATLAS vs. CMS:
twice the size
half the weight

Different B field

Same coverage
tracker & calorimetry,
same cost

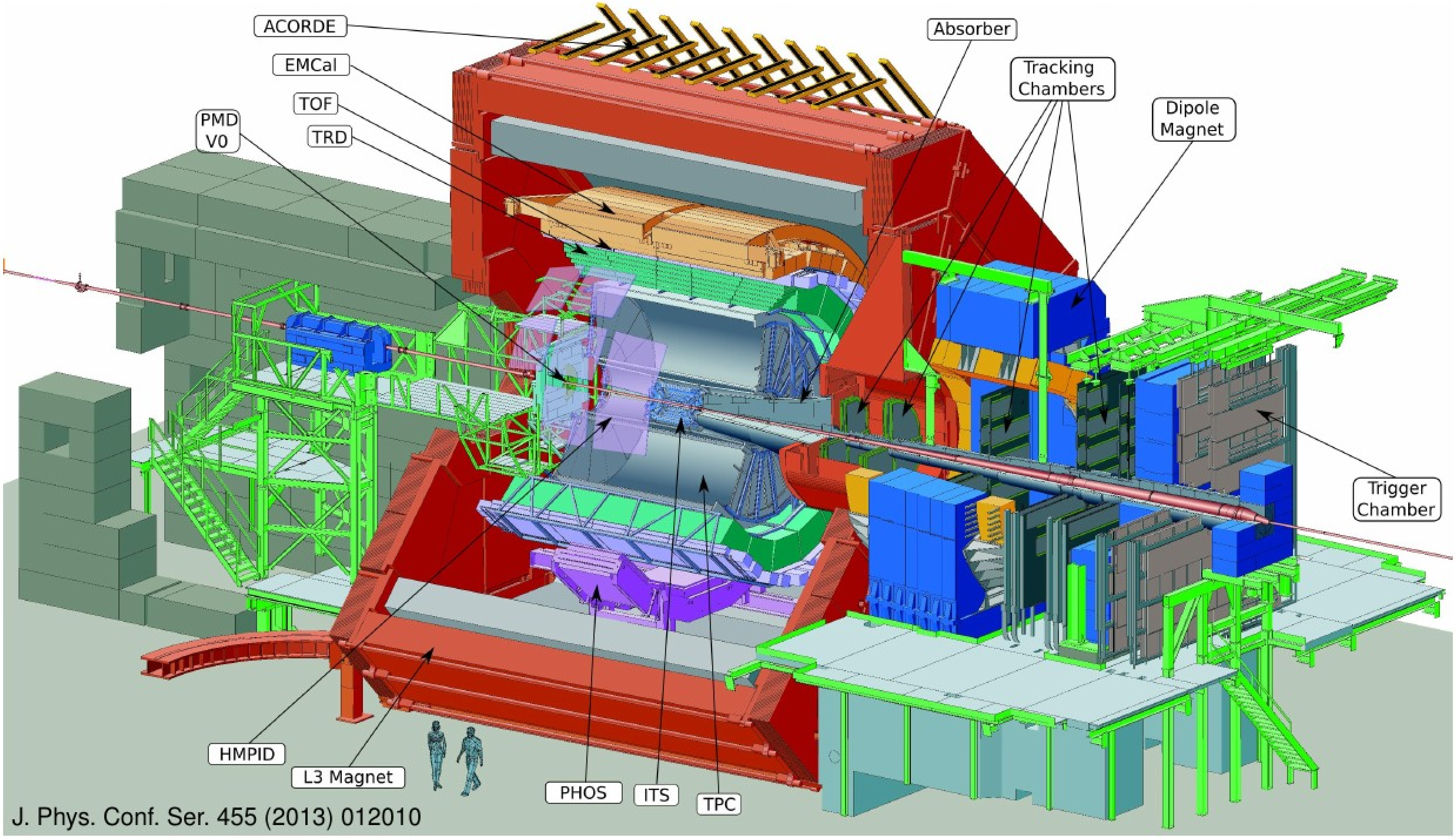
LHCb: optimized for B physics



Int. J. Mod. Phys. A30 (2015) 07, 1530022

precision measuremnts in forward direction

ALICE: optimized for high-multiplicity events



exotic states of matter and quark-gluon plasma

Event reconstruction

Optimal combination of different information needed:

- momentum measurement in tracking system, energy in calorimeters

$$\Delta p_T / p_T \propto p_T \qquad \Delta E / E \propto 1 / \sqrt{E}$$

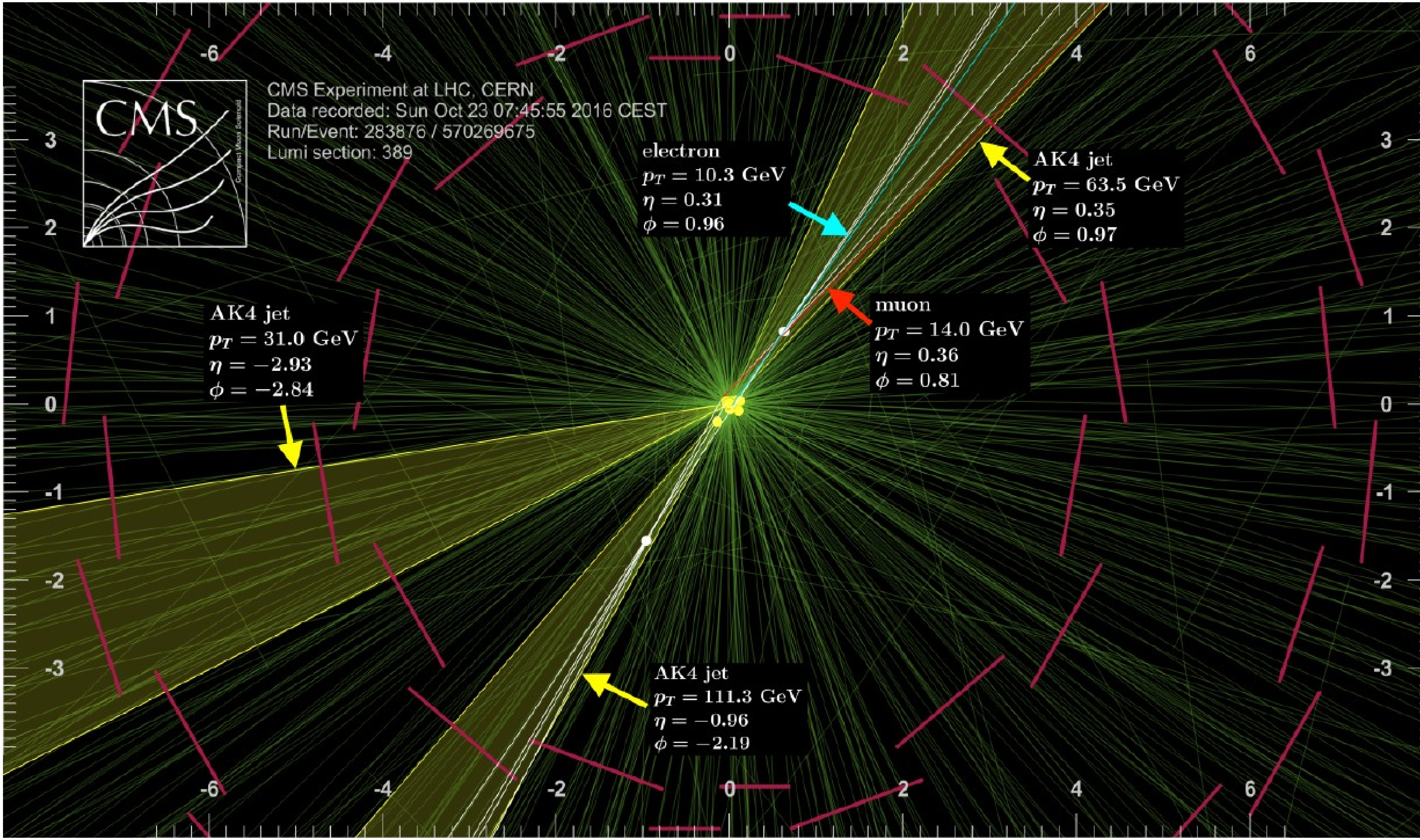
- for muos: combine track parameters from central detector and from myon system
- recognise converted photons, use tracks for better direction measurement
- assign (possibly) all tracks to clusters of energy deposits in calorimeters (reconstruction of „Particle Flow“)
- particle detection from range, shower parameters, dE/dx, secondary vertices, ...
  for known particle types (=mass) momentum and energy are related: $E^2 = p^2 + m^2$
- instable particles are reconstructed from stable decay products (invariant relativistic mass)
- combine all particles to Jets
- detect non-interacting particles (neutrinos, particles from “new physics”) via „missing transvers momentum“ or „missing transverse energy“

$$\vec{p}_{T\,miss} = -\sum_i \vec{p}_{T\,i}$$

This only works if interaction point is hermetically surrounded by detector components !

Selected detector components

Tracking detector



cern.ch

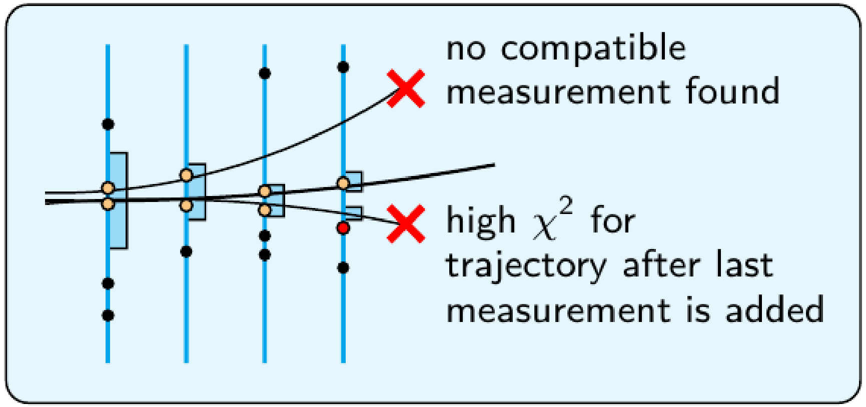
Purpose: registration of all energy deposits from charged particles, precise determination of their position, possibly measure dE/dx

Exasmples of Tracking Detectors

- ***Gaseous*** detectors
  - Prototype: Geiger counter
  - Various types, e. g. ***multi-wire proportional chamber, drift chamber, time projection chamber***
- ***Semiconductor*** detectors
  - Examples: ***silicon strips and pixel*** detectors (cf. lab exercises)
  - Further application e. g. precise energy measurement with germanium detectors
- ***Performance*** characteristics of tracking detectors
  - ***Single-hit position resolution***
  - ***Momentum resolution***

Track and vertex reconstrucion

- Measurement of particle track: tracking detector with ***several sensitive layers***
- Electric signal in each layer: ***hit***
- Track reconstruction ('tracking')
  - ***Track finding*** (pattern recognition): do hits belong to same helix?
  - ***Track fitting*** (parameter estimation): which helix parameters match the data best?
- ***Vertex fit***: do tracks originate from same origin ('vertex')?



G. Mittag

Track fitting: minimise

$$\chi^2 = \sum_{\text{hit}} \frac{(x_i - f_i(\mathbf{q}))^2}{\sigma_i^2}$$

x_i : measured hit position

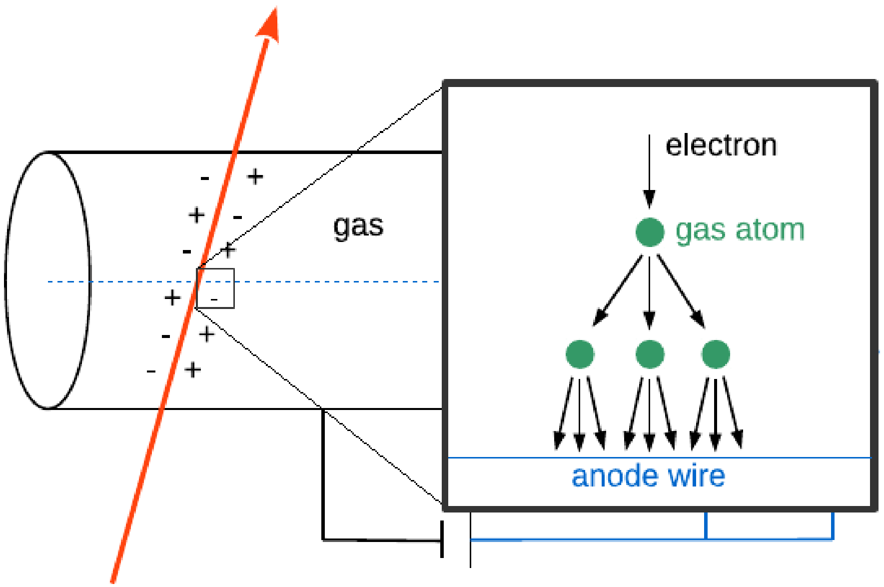
$f_i(\mathbf{q})$: track model

σ_i : measurement uncertainty

Gaseous Detectors: principle

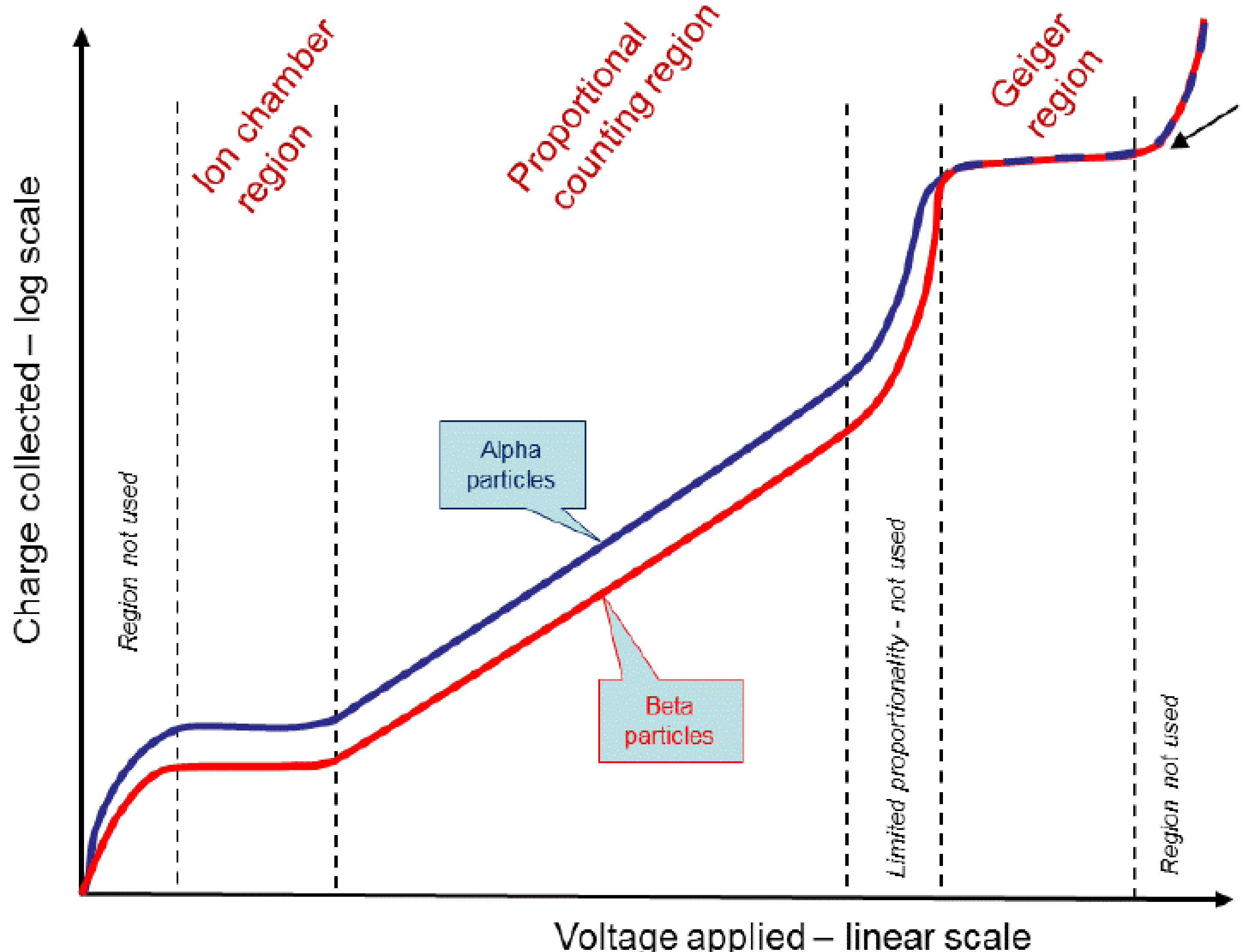
Important basic example: ***proportional counter***

- Traversing charged particle ***ionises*** inert ***gas***
- High voltage between anode wire and cylinder: drift of light electrons and heavy ions to electrodes (charge separation)
- Electric field large close to anode wire: ***charge amplification*** (typical factor $10 \cdot 10^5$) in ***Townsend avalanche***



- Design: each original ionisation event produces only one avalanche → output proportional to energy of incident particle
- Ions emit UV photons when recombining → further ionisation limiting proportionality: absorbed by ***quench gas***, e. g. CO_2

Gaseous Detectors: amplification

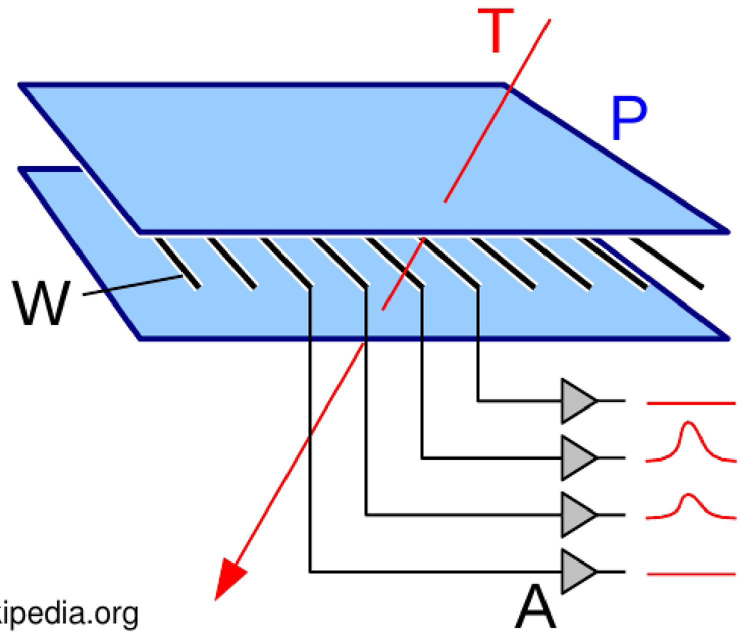


wikimedia.org

Multi-wire proportional chamber

Gorges Charpak 1968, Nobel Prize 1992

- Many anode ***wires in parallel***, operated in proportional region
  - Planar arrangement of proportional counters without separating walls
  - Typical dimensions: $\mathcal{O}(100\,\mu\text{m})$ diameter, $\mathcal{O}(1\text{ mm})$ wire distance
- Electric field: radial in vicinity of wire (avalanche), homogeneous far away
- Wire with signal $\rightarrow$ 1D position information
  - Single-hit spatial position resolution $\sigma_x = d/\sqrt{12}$



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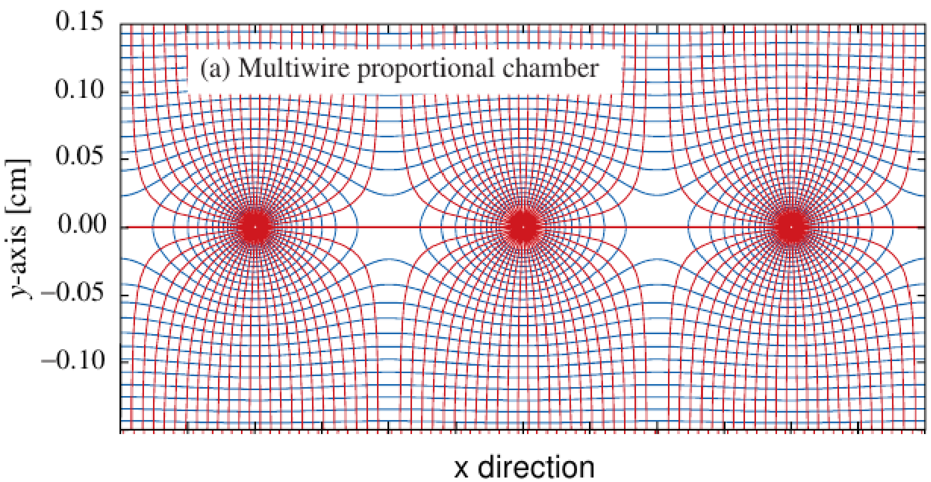
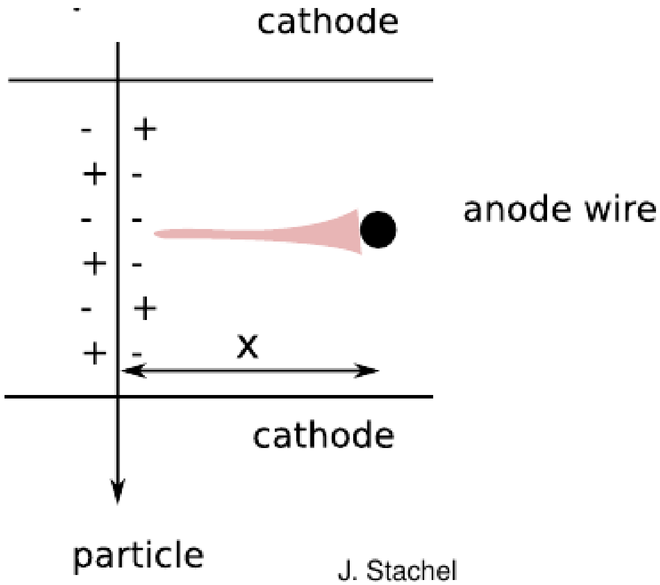


pdg.lbl.gov

Drift Chamber

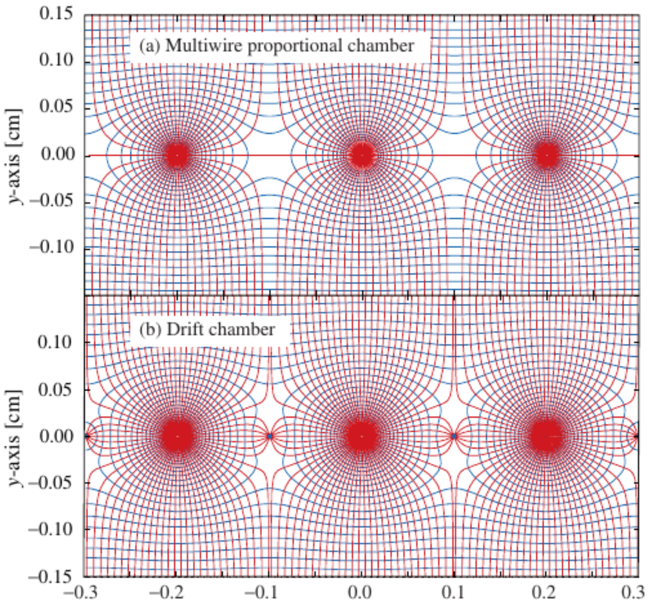


drift time of charges used determine
distance of track from anode wire

- precise shaping and knowledge of electrical field and properties of gas
- spacial resolution limited by drift-time variations (diffusion!)

→ spatial resolutions of ~50 μm possible

Improvement of field quality by additional **field wires**



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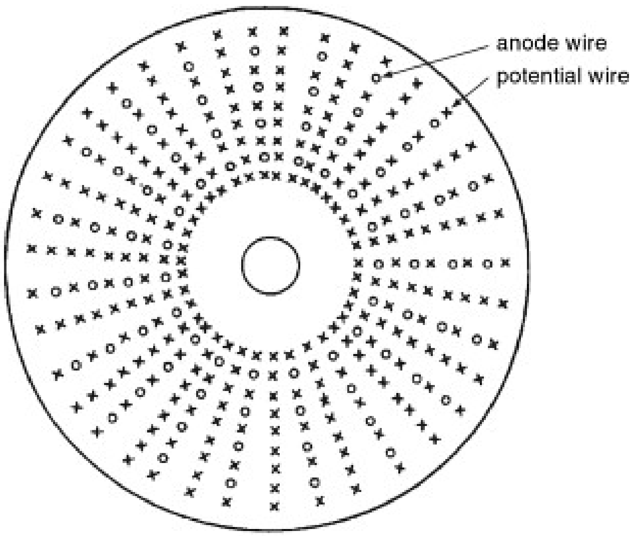
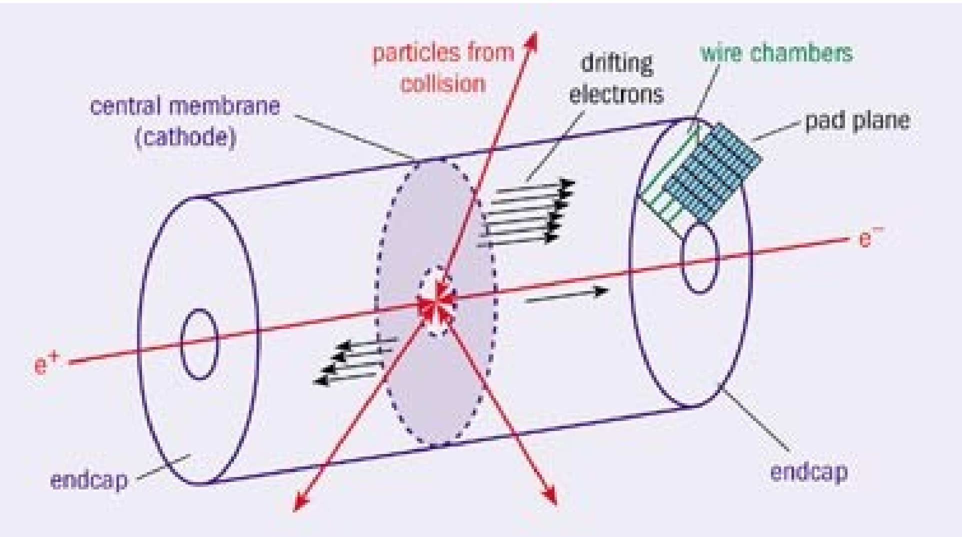
Types of Drift Chambers

Cylindrical drift chamber



Jet Chamber of the OPAL experiment

Time Procjection chamber (TPC)

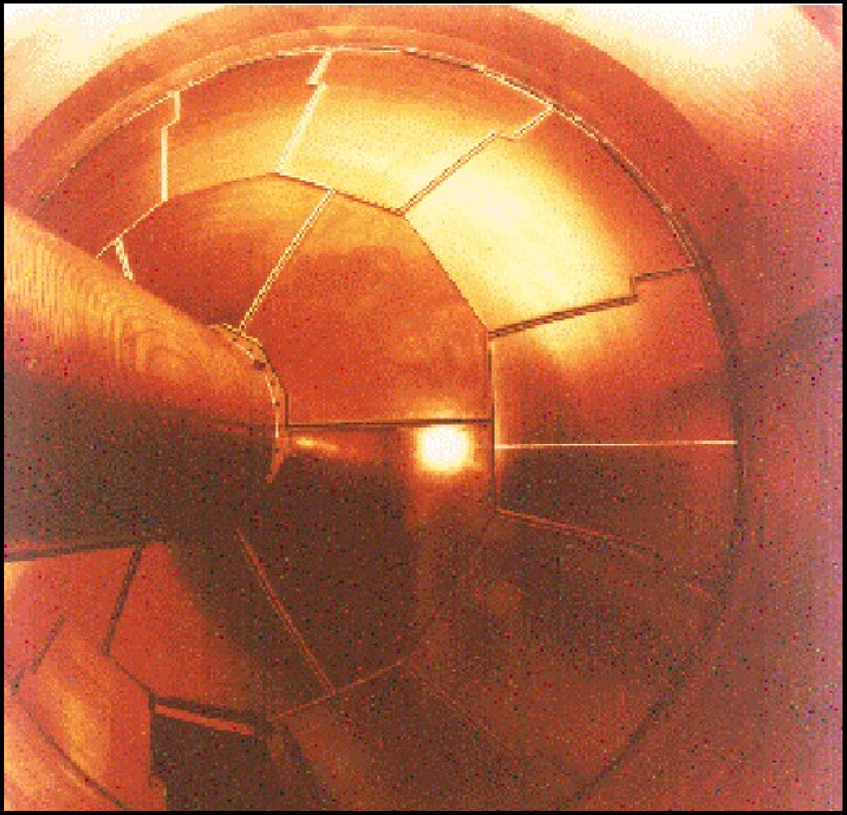


CERN Courier, Jan. 2004

Electrical field parallel to B-Field
limits diffusion along long drift path

+ excellent position resolution
+ excellent dE/dx resolution
- long drift times → low rates

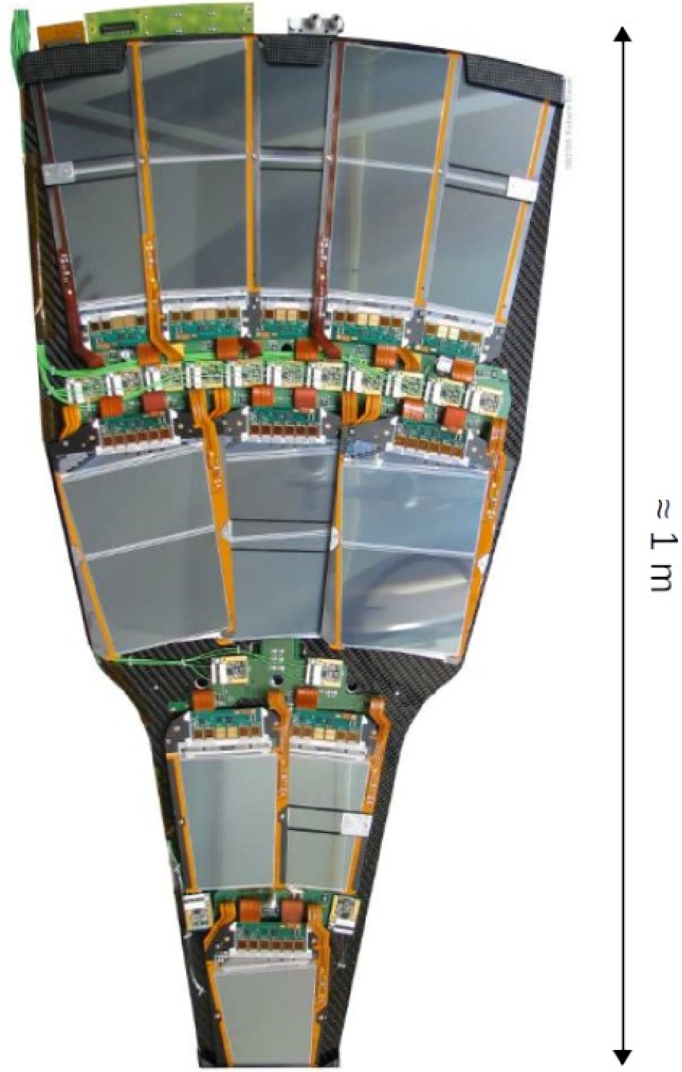
View into ALEPH TPC



Semiconductor Detectors

- Working principle: ***semiconductor ionisation chamber***
  - Detector = diode in reverse bias
  - Most common design: ***hybrid detector***
    - Ionisation and charge collection in silicon sensor
    - Amplification in ***separate read-out chip***
- Typical segmentation
  - 1D ***microstrips***
    (pitch: 25–200 µm, length: 10 cm)
  - 2D ***pixel***
    (ATLAS: $50 \times 400\,\mu m^2$, CMS: $100 \times 150\,\mu m^2$)

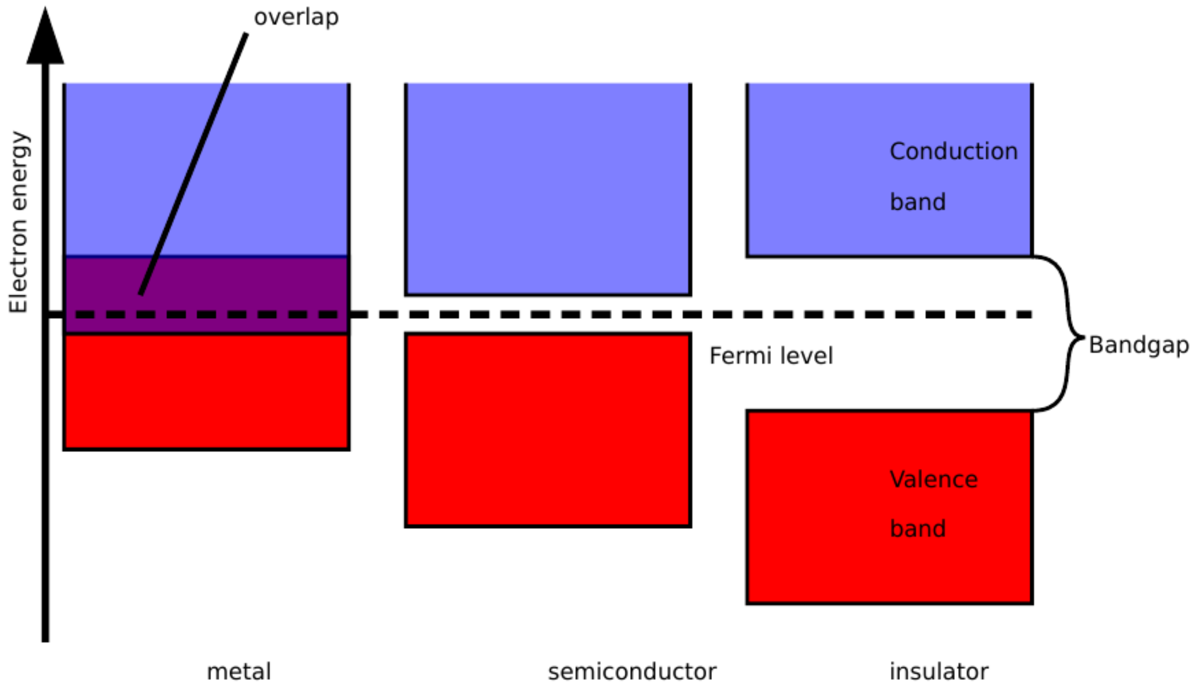
part of the CMS silicon strip detector



JINST 5 (2010) P06007

Principle of Semiconductor Detectors

- Reminder: electronic band structure
  - Electrons in crystal lattice $\equiv$ periodic potential $\rightarrow$ ***Bloch states***
  - Many atoms: energy levels overlap $\rightarrow$ quasi-continuous ***energy bands*** with ***band gaps***
  - (Intrinsic) ***semiconductors***: small band gap ($\lesssim$ 5 eV) between valence and conduction band, e. g. effectively 3.6 eV for silicon



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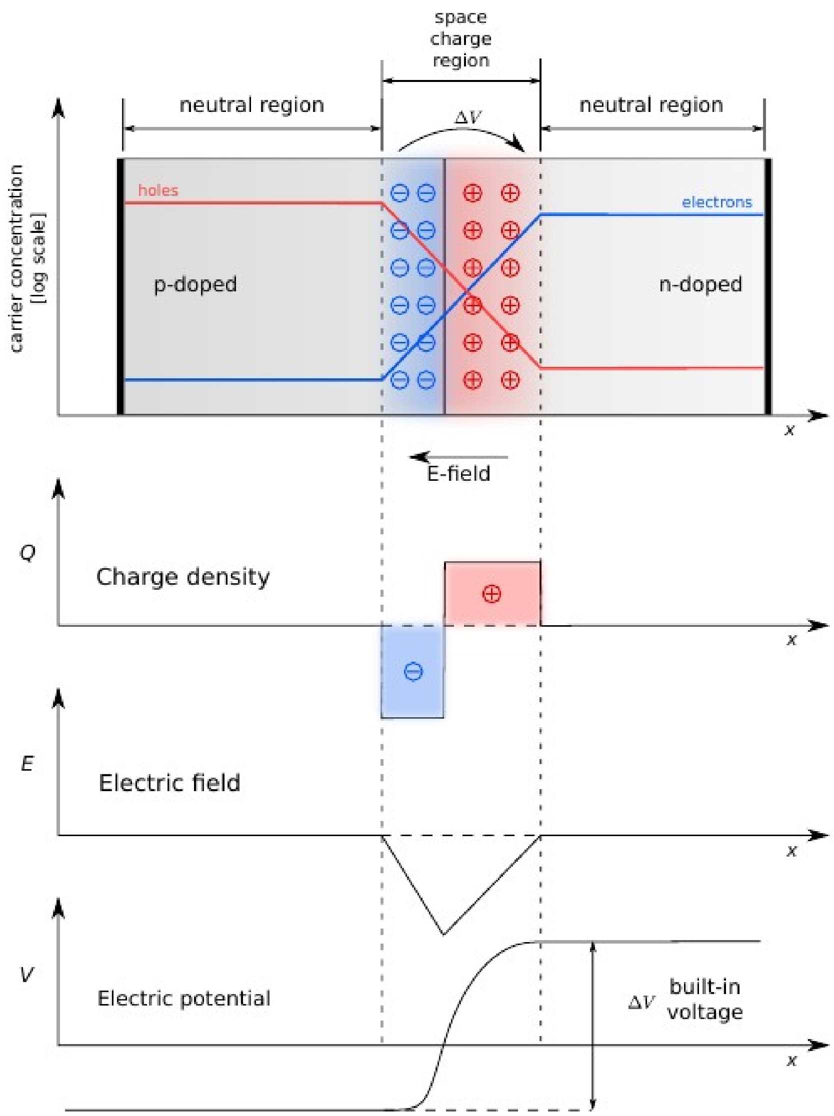
Depletion Zone in pn Junction

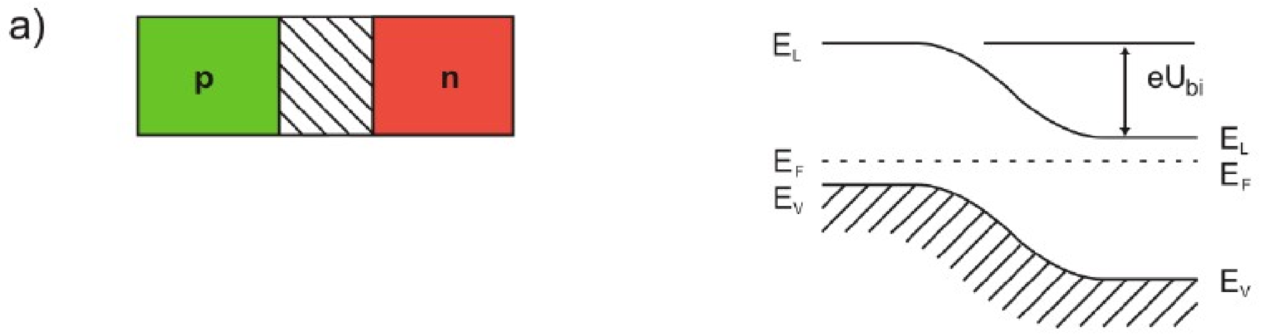


wikipedia.org

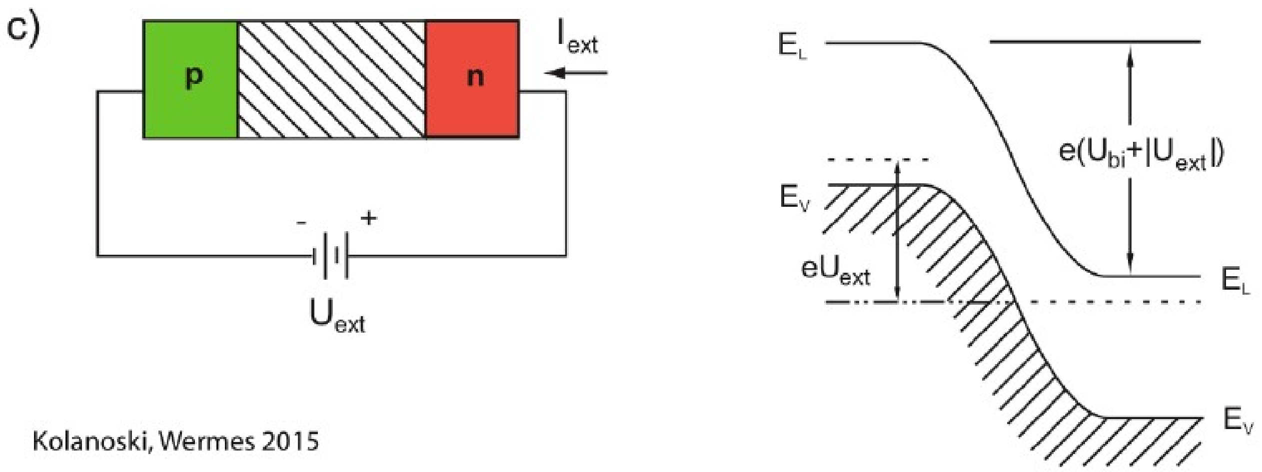
- Boundary between p- and n-doped semiconductor
  - Majority charge carriers ***diffuse*** to other side and ***recombine***
  - Charge-density gradient → E field (***'built-in' voltage*** ≈0.6–0.7 V) counteracts diffusion
  - Formation of ***non-conductive zone*** depleted of charge carriers (***depletion zone***)
- Charged ***particle traversing depletion zone***: creation of ***free charges by ionisation*** → electric current, signal

Biased pn Junction

- pn junction without external bias voltage



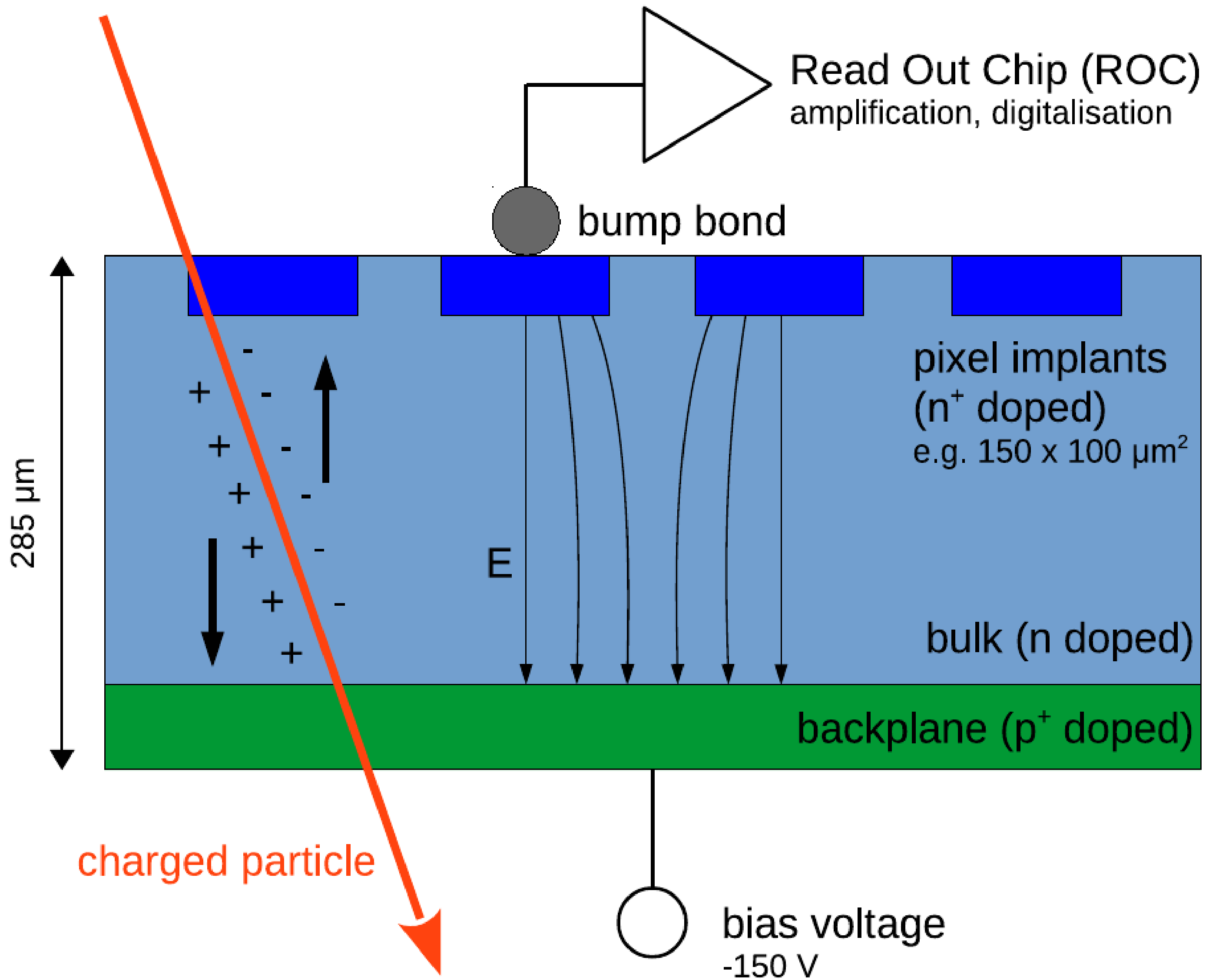
- pn junction with external ***reverse bias voltage***
  - External voltage with negative terminal applied to p-type region: further removal of charge carriers $\rightarrow$ ***increased depletion zone***



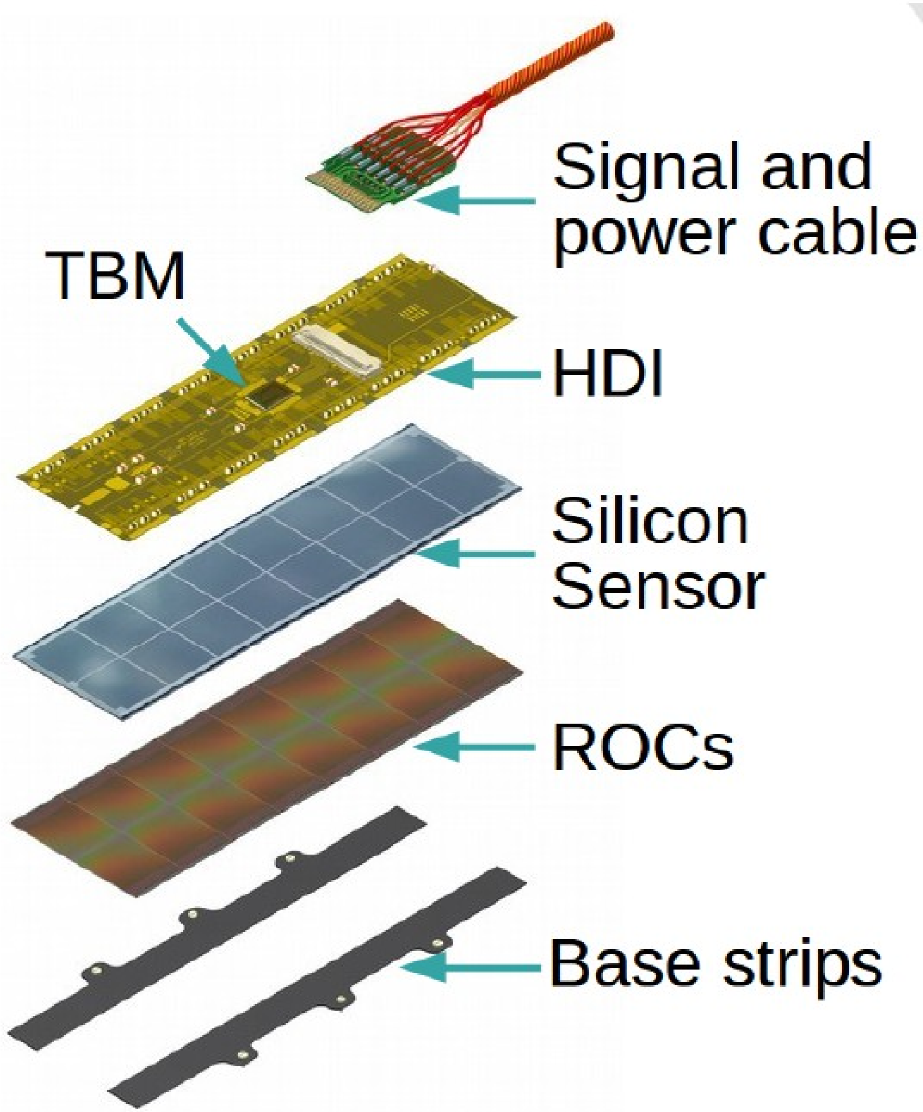
Kolanoski, Wermes 2015

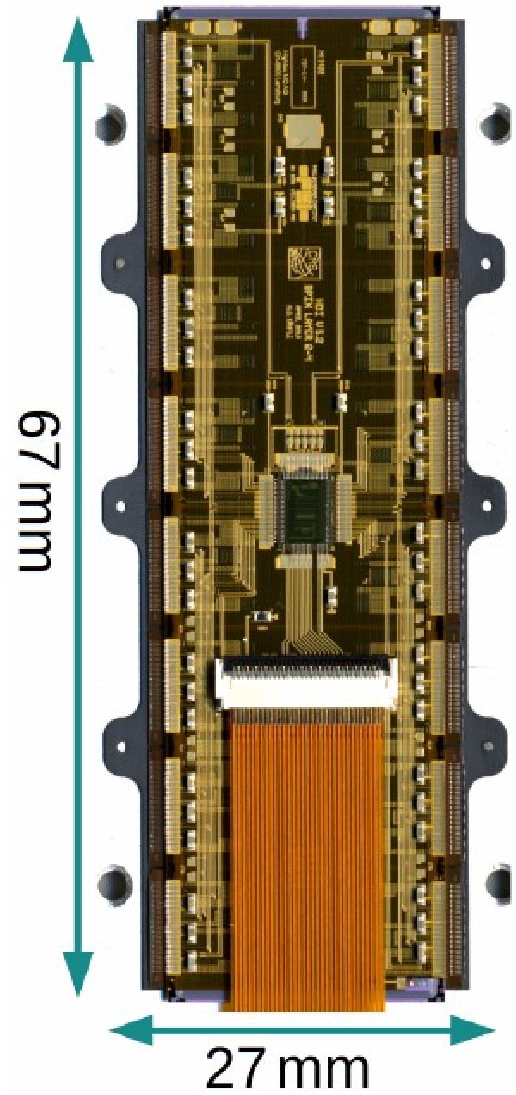
Principle of Semiconductor Detectors (2)

Example: CMS Pixel Sensor

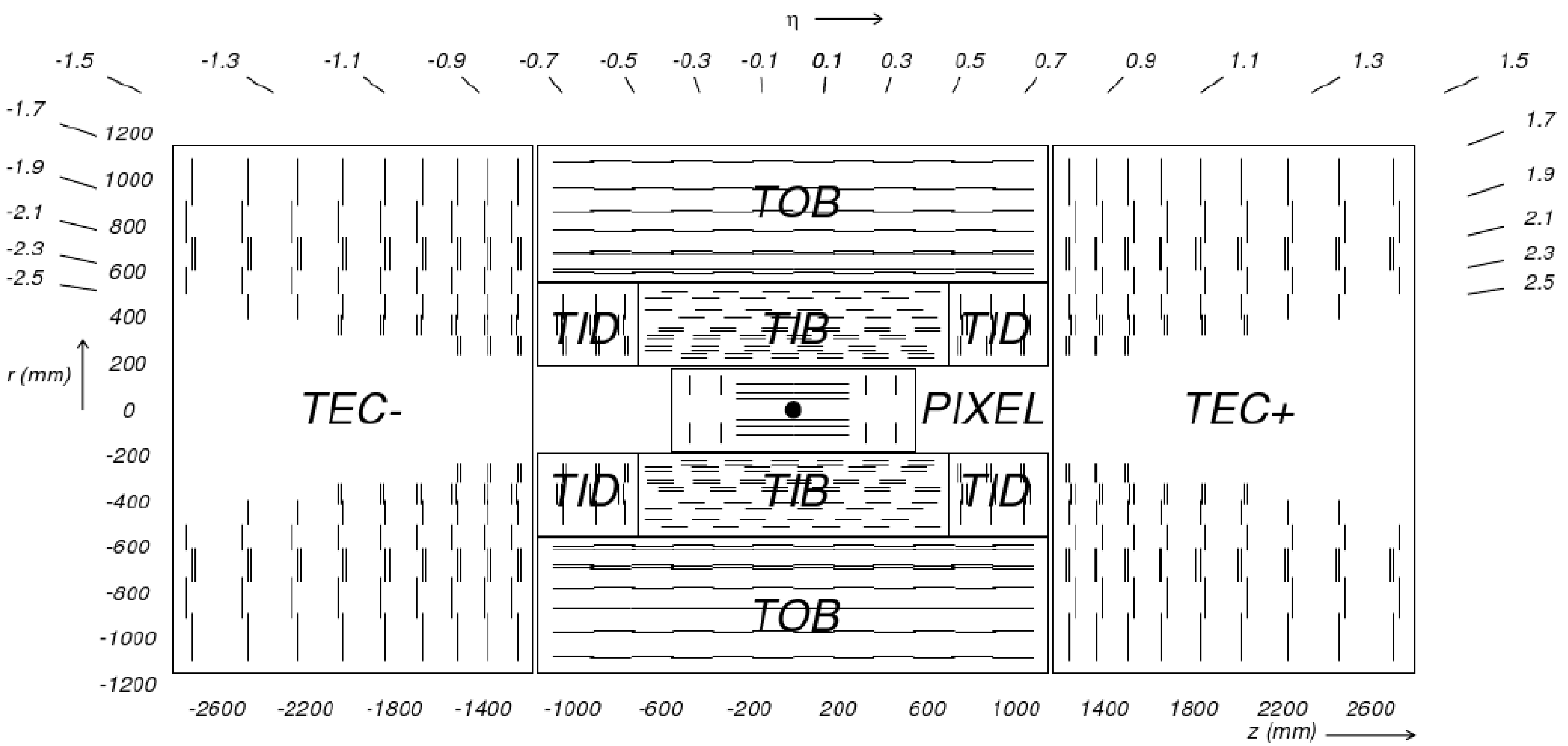


Example: CMS Pixel Module





Example: CMS Silicon Tracker



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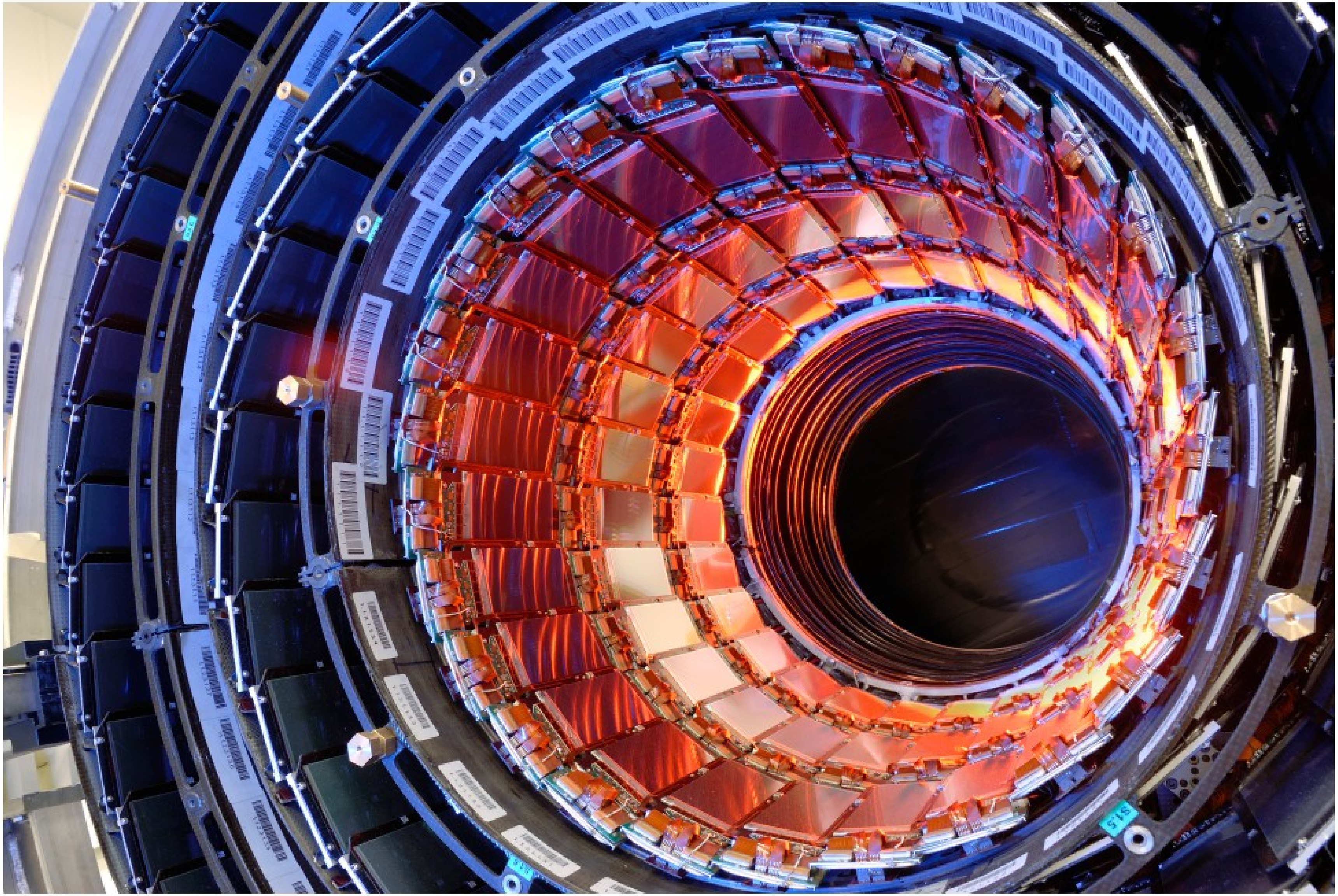
- Entire tracking detector from silicon: more than ***200 m² sensitive area***
  - Approximately 25 000 sensors, 75 million channels
  - Inner layers: ***pixel detectors*** $\rightarrow$ high resolution (up to $\sigma_x = 10\,\mu\text{m}$)
  - Outer layers: ***strips detectors*** $\rightarrow$ large coverage

Example: CMS Silicon Tracker



CERN

CMS Barrel Strip Detector

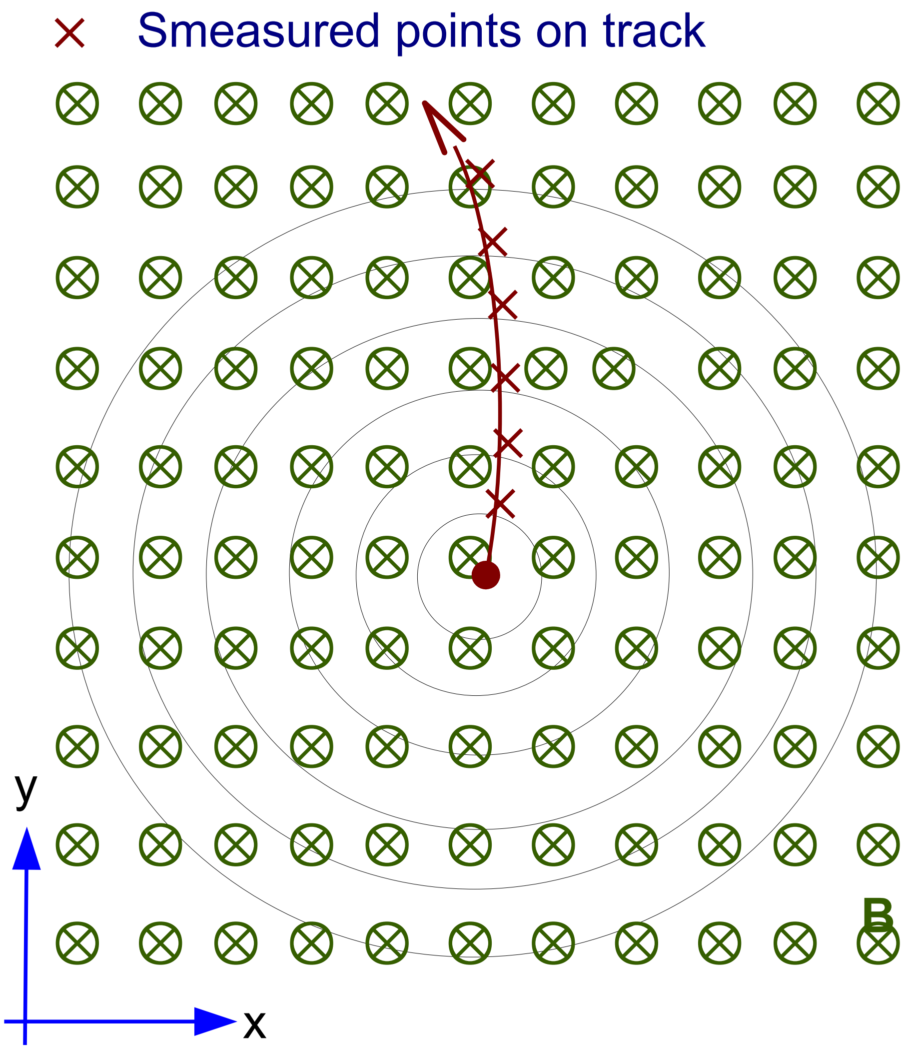
Comparison

gaseous detectors	*silicon detectors*
high ionisation energy: $\approx$ 30 eV per electron-hole pair	low ionisation energy: 3.6 eV per electron-hole pair $\rightarrow$ ***larger signal***, better energy resolution (S/N)
relatively slow signal: drift velocity $\mathcal{O}(\mathrm{cm}\,\mu\mathrm{s}^{-1})$	fast signal: $\mathcal{O}(\mathrm{ns})$
many hits but limited granularity (wire distance)	few hits with high granularity
low material budget	***higher material budget*** affects measurement (multiple scattering, conversion, . . .)
ages under radiation	radiation damages well under control

- Applications (strongly simplified)
  - Silicon detectors: ***highest rates***, e. g. LHC
  - Gaseous detectors: ***highest precision***, e. g. B factories, future International Linear Collider (ILC)
- Often: ***combination*** of silicon detectors close to interaction point and gaseous detectors at larger distance

Momentum Measurement

Many layers of tracking detectors in homogeneous magnitic field



tracks from charged particles with transverse momentum p_t form arcs with bending radius R:

Lorentz force: $\vec{F_L} = q\,\vec{v} \times \vec{B}$

centripetal force: $F_Z = m\,\vec{v}^2 \,/\, R)$

$$\Rightarrow |\vec{p_t}| = q\;B\;R$$

note: this is also valid relativistically

Rem.: 1.) due to z component of momentum, tracks have form of a thre-dimensional spiral („helix“)

2.) practile form of avove equation for q = e :

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

Momentum Measurement: sources of uncertainty

Uncertainties on points of track (σ_{xy} resp. $\sigma_{r\varphi}$) lead to
uncertainty on transverse momentum:
two main contributions:
- spacial resolution of detector – *depends on track momentum*
- multiple scatterig – *almost constant*

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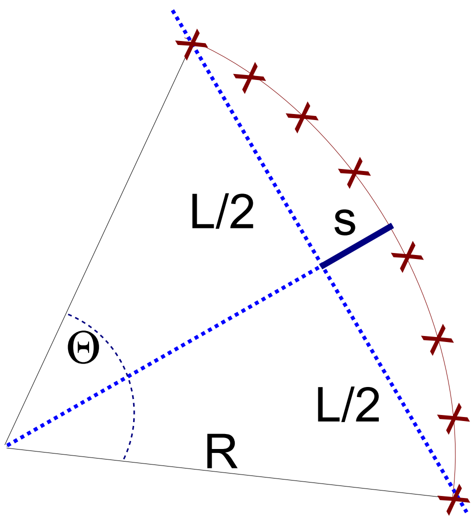
contribution of detector resolution (simple, analytical consideration) :



bending radius determined by measuremet of **sagitta** s given a track lengh ~L in the detector

$$s = 2\,R\,\sin^2\frac{\Theta}{4} \simeq \frac{L^2}{8R}$$

measured quantity is the curvature ρ = 1/R of the track with an approximately gaussian uncertainty:

$$p_t = qB/\rho \Rightarrow \frac{\Delta_{p_t}}{p_t} = qB\frac{\Delta_\rho}{\rho} = p_t\Delta_\rho \Rightarrow \boxed{\frac{\Delta p_t}{p_t^2} = \Delta\rho \simeq \text{const.}}$$

Momentum Resolution

in more detail:

uncertainty on sagitta (Glückstern, NIM 24 (1963)) for >10 track points N:

$$\Delta_s = \sqrt{\frac{A}{N+4}} \cdot \frac{\sigma_{xy}}{8}$$, statistical factor A = 720

leads to:

$$\frac{\Delta_{p_t}}{p_t} = \frac{8\,p_t}{0.3BL^2} \cdot \Delta_s$$

Precision increases with square root of the number of measurements, but quadratically with track length

Large detector with high magnetic field more important than many points !

BL^2 is an important property of a tracking system

ALEPH: R=2 m, B = 1,5 T → BL^2 = 4,5 Tm^2,
21 points/track → $\Delta p_t/p_t$= ~10^{-3} p_t [GeV/c]
CMS: R= 1,2 m, B=1,8 T → BL^2=5.5
10-14 points/track → $\Delta p_t/p_t$= ~10^{-3} p_t [GeV/c]

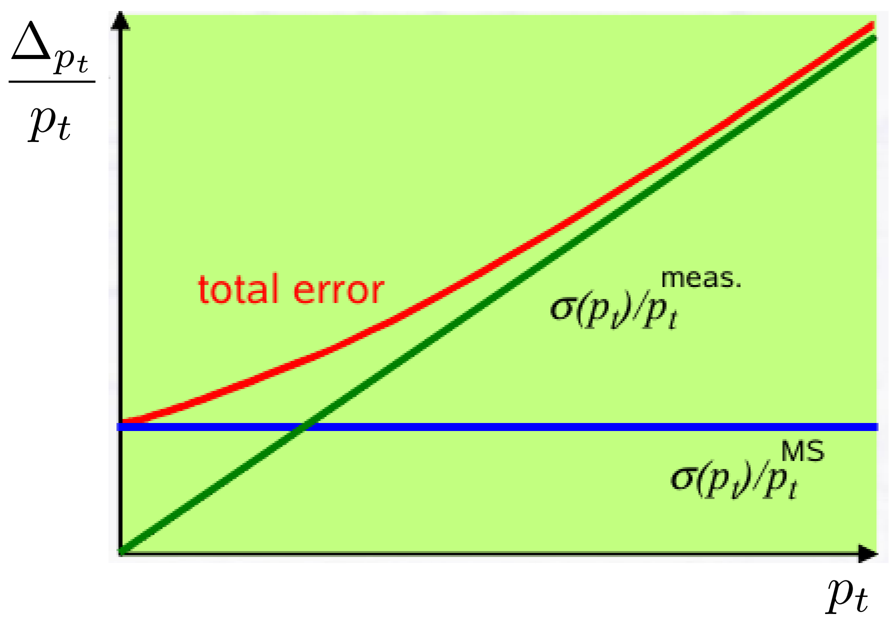
Momentum Resolution

there is a ~constant contribution from **multiple scattering** to momentum resolution

$$\Theta_{MS} \propto \frac{1}{p_t}\sqrt{\frac{L}{X_0}}$$

$$\frac{\Delta_{p_t}}{p_t} \propto p_t \Delta_{xy} \quad \Rightarrow \left(\frac{\Delta_{p_t}}{p_t}\right)_{MS} \propto p_t\,\Theta_{MS} = \text{const.}$$

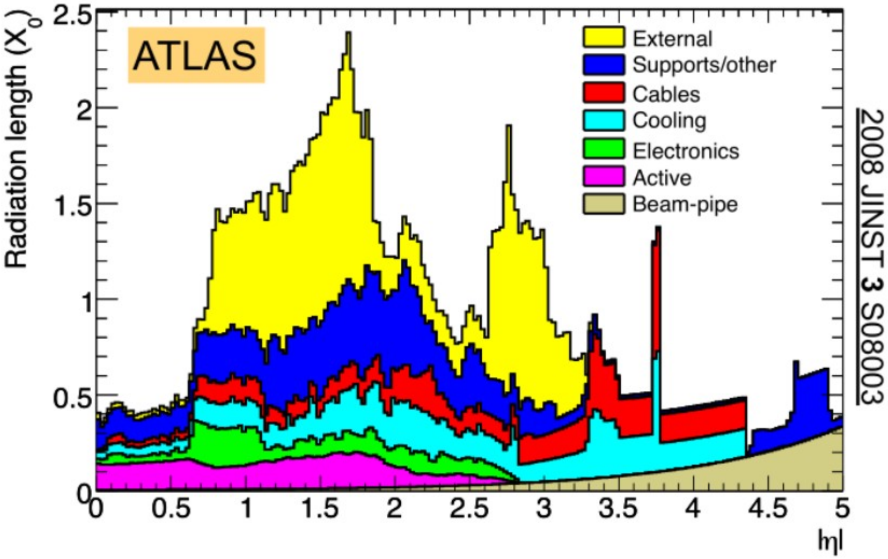
multiple scattering in decector leads to p_t - independent contribution to uncertainty



$$\frac{\sigma_{p_T}}{p_T} = \underbrace{\frac{a}{BL^2}\cdot\sigma_x\cdot p_T}_{\text{hit resolution}} \oplus \underbrace{\frac{b}{B\sqrt{LX_0}}}_{\text{multiple scat.}}$$

Remark.:
track parameters of modern detectors are determined by fit to all points including material effects (energy loss, deflection)

Material budget of tracking detectors



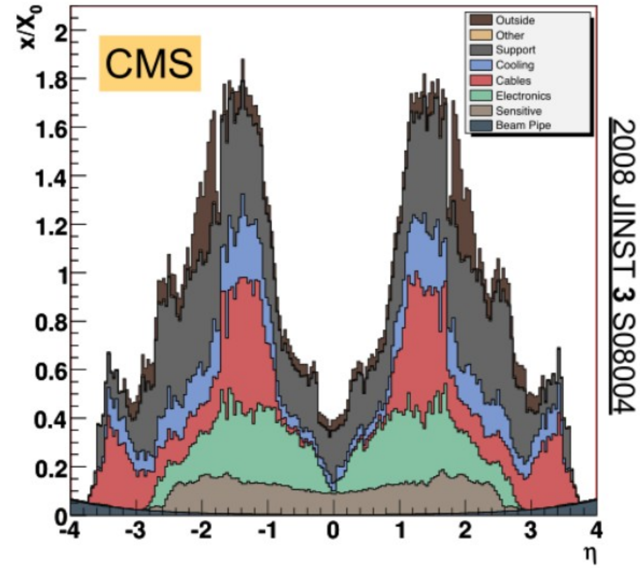


TABLE 5 Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

Date	ATLAS $\eta \approx 0$	$\eta \approx 1.7$	CMS $\eta \approx 0$	$\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50

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Material in or in front of tracking detectors leads to :

- multiple scattering
- photon conversions
- early start of em showers

B-Tagging

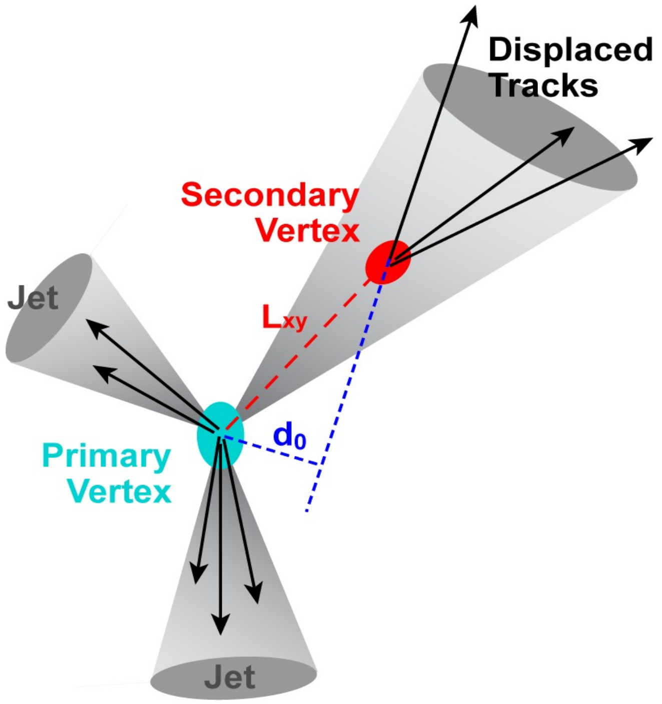
Identification ("tagging") of hadrons with b- und c- quarks or of $\tau^{\pm}$ leptons leptons with high-resolution tracking detectors:

– measurement of flight distance L_{xy} in xy plane

– measurement of impact parameter d_0 of tracks

(– leptons from semileptonic b decays are also important signature, as well as invariant jet mass or jet shape)

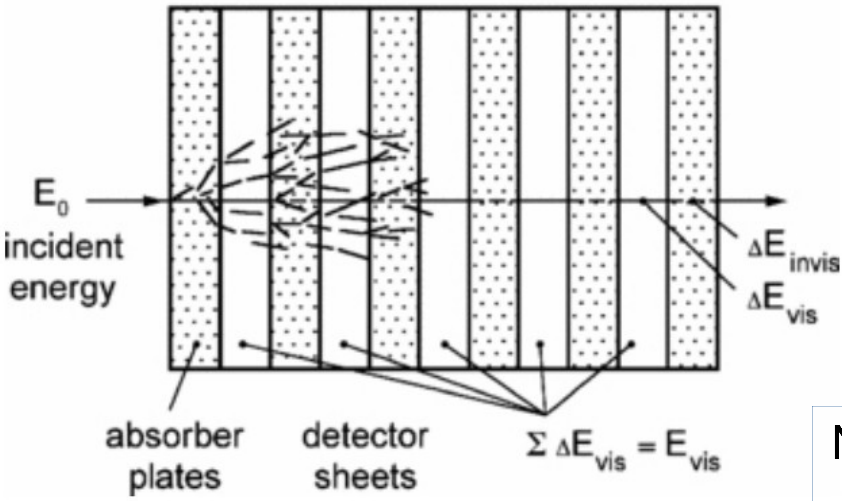
use multivariate methods for simultaneous analyis of all sensitive variables



L_{xy} and d_0 have a very high impact !

→ motivation for high-precision vertex detectors

Calorimeters



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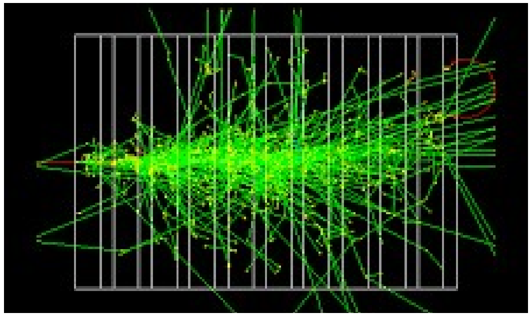


Simulated shower with Geant4

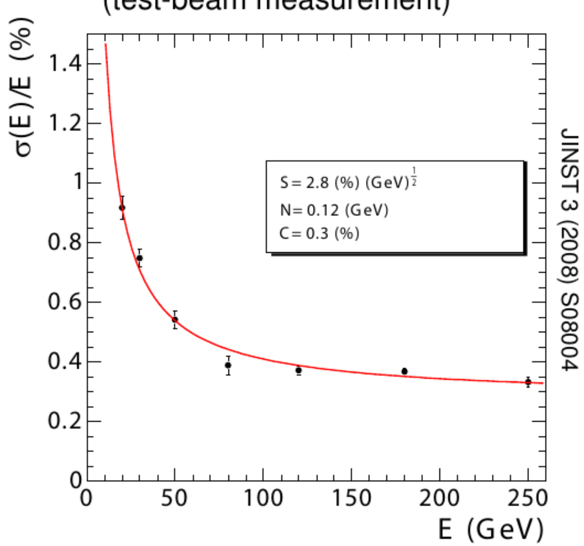
Number of secondary particles in shower proportional to particle energy
→ **statistical fluctuations** ~√N , i.e. ~√E

Energy resolution of calorimeters parameterized as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Stochastic term: fluctuations in shower development and sampling (Poisson statistics)
- Noise term: noise in readout electronics
- Constant term: calibration, 'leakage' out of calorimeter

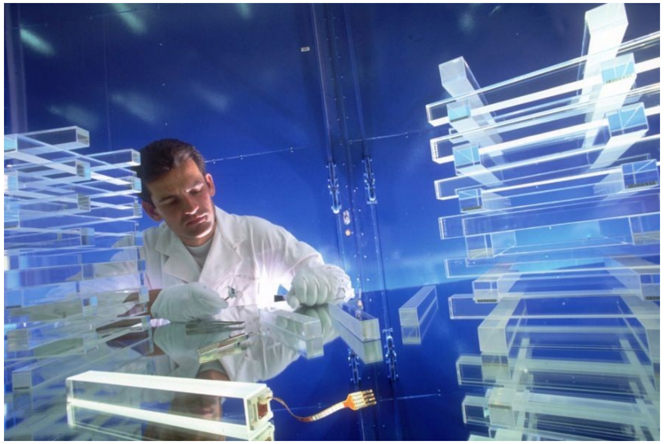
Energy resolution of CMS ECAL (test-beam measurement)



Example: CMS $PbWO_4$ Crystal Calorimeter

Homogeneous calorimeter: lead-tungstate ($PbWO_4$) crystal scintillators

- Radiation length $X_0 = 0.89\,\mathrm{cm}$, Moliére radius of 2.2 cm
- Achieves ***very good energy resolution***: stochastic term 3 %

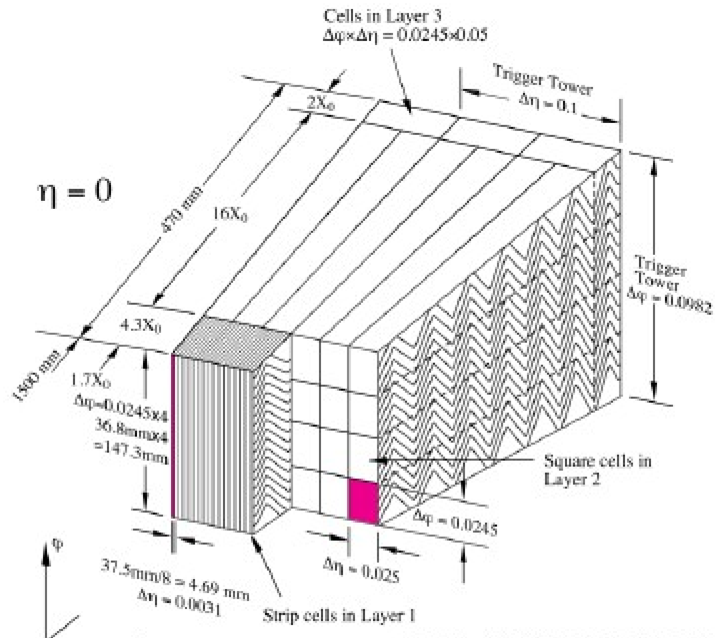


cms.web.cern.ch

- ***Low scintillation light yield*** ($\approx$ 30 photons per MeV): challenge to readout, requires high amplification in photodetectors (increased noise)
- Yield ***strongly temperature dependent***: 2 %/°C at 18 °C
  $\rightarrow$ temperature kept stable within 0.1 °C to retain energy resolution
  - Controlled by integrated laser calibration system

Example: ATLAS Liquid Argon Calorimeter

- Sampling calorimeter: active material liquid argon
  - ***Ionisation*** by charged shower particles (26 eV per electron-hole pair)
  - Ions drift to electrodes (voltage $\mathcal{O}(1000)$V) $\rightarrow$ electric signal
  - Operation temperature $\approx$ 80 K
- Example: ATLAS ECAL
  - ***Absorption*** of em showers in ***lead tiles***
  - Special feature: ***accordion structure*** $\rightarrow$ fast readout, no gaps in detector coverage



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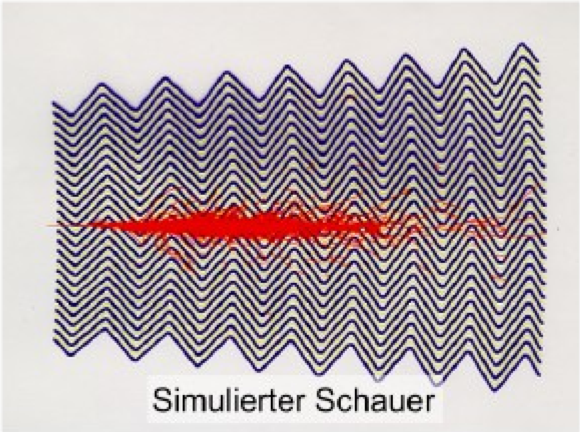

Design Goals of Calorimeters

- Precise energy measurement (and identification) for electrons, photons, jets, and missing transverse energy
  - High intrinsic ***energy resolution***
  - High ***granularity***, ***hermetic*** coverage ('4π' detector)
  - ***Depth***: many radiation lengths (ECAL) resp. interaction lengths (HCAL)
    - Otherwise: 'leakage' of shower out of calorimeter (for jets also called 'punch through')
- Possibly usage in trigger system (online data selection)
  - ***Fast*** readout $\mathcal{O}$(ns)

- ***Homogeneous calorimeters***
  - ✓ All energy deposited in active material: ***best resolution***
  - ✗ Require advanced materials: often more ***expensive and heavier***
  - ✗ Often very ***low light yield***: challenge to readout
- ***Sampling calorimeters***
  - ✗ Some of the energy deposited in absorber: ***limits resolution***
  - ✓ Absorbing and active material can be specifically chosen: more ***flexible and cheaper design*** choices

Comparison: ATLAS and CMS

	ATLAS	CMS
Position	***Outside*** of magnet coil: 2–4 X_0 additional material in front of ECAL	***Inside*** magnet coil: Limited depth (HCAL only 7.2 λ_I at $\eta = 0$: additional 'tail catcher')
ECAL	Lead/liquid-argon (LAr) ***sampling calorimeter***: high ***granularity*** and longitudinal resolution	***Homogeneous*** crystal calorimeter ($PbWO_4$): high ***intrinsic energy*** ***resolution***
HCAL	***sampling calorimeters***: iron+scintillator (barrel) copper+LAr (endcap)	***sampling calorimeters***: brass+scintillator (barrel+endcap) iron+quartz fibres (forward)

Energy resolution: ATLAS vs. CMS

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Calorimeter	Term	ATLAS	CMS
ECAL (barrel)	stochastic (a)	$10\,\%\sqrt{\mathrm{GeV}}$	$3\,\%\sqrt{\mathrm{GeV}}$
	noise (b)	250 MeV	200 MeV
	constant (c)	0.2 %	0.5 %
ECAL+HCAL (barrel)	stochastic (a)	$55\,\%\sqrt{\mathrm{GeV}}$	$70\,\%\sqrt{\mathrm{GeV}}$
	noise (b)	3.2 GeV	1.0 GeV
	constant (c)	2.3 %	8 %

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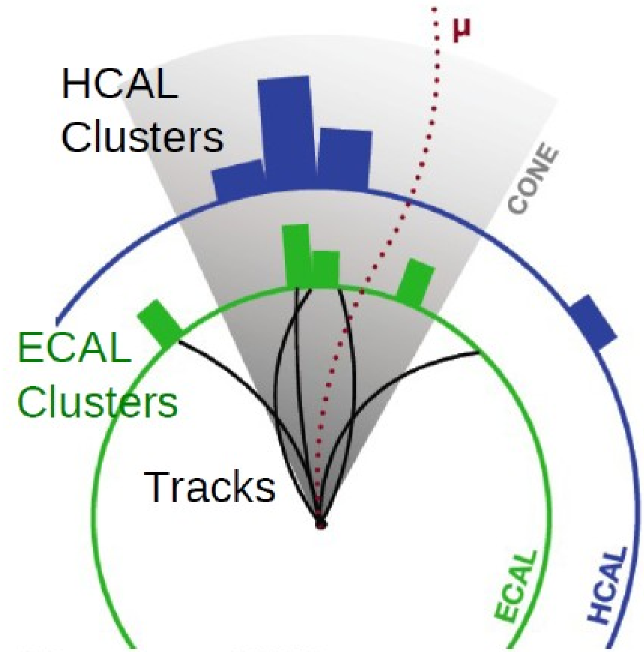
Reconstruction of "Particle Flow"

Particle-flow reconstruction: identification and measurement of ***individual particles*** by optimal ***combination*** of information from ***different subdetectors***

- Effective usage of subdetectors (very simplified!)
  - Tracker: momentum of charged particles
  - Muon system: muon ID (and momentum)
  - ECAL: photon energy
  - HCAL: neutral hadron energy
    $\rightarrow$ only $\approx 10\,\%$ of jet energy
- Jets reconstructed from particle candidates: much ***better energy resolution***



F. Beaudette at ICHEP2010

particle flow

$$E_{\text{jet}} = E_{\text{tracks}} + E_{\gamma} + E_{\text{n}}$$

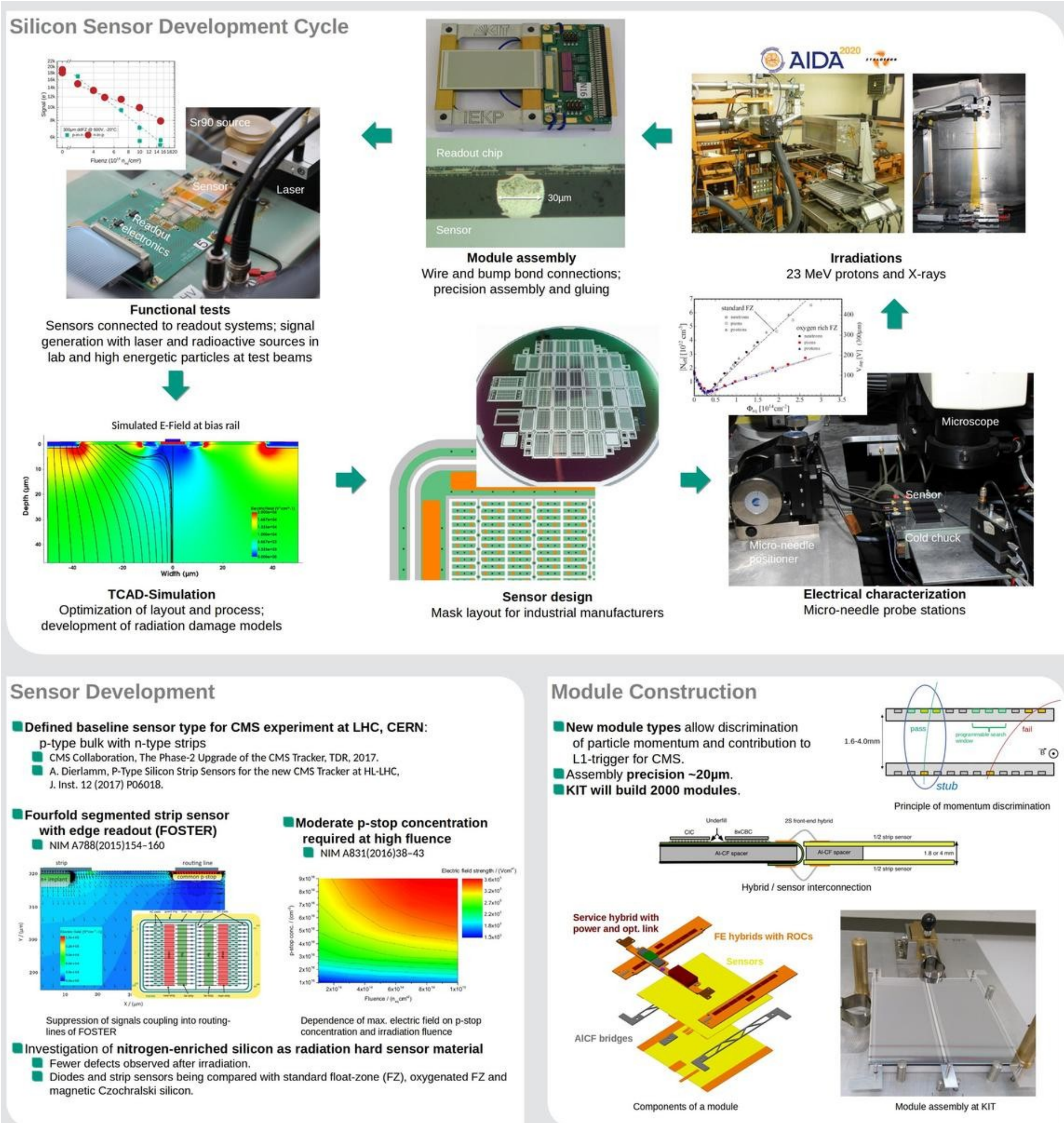
- Particle-flow: requires strong magnet field / high granularity (CMS!)

Relevant in particular for jet reconstruction and missing energy

Opportunities @ KIT

KIT is strongly involved in the **upgrade** of the **CMS detector** for the LHC high-luminosity phase

Groups of
- Prof. U. Husemann
- Prof. M. Weber



see lecture

"*Detektoren für Teilchen- und Astroteilchenphysik*"

by Frank Hartmann

(CMS upgrade coordinator)