

Praktikum PR 141.A46

# Experimentelle Methoden der Hochenergiephysik

T. Bergauer

18 Oct 2018

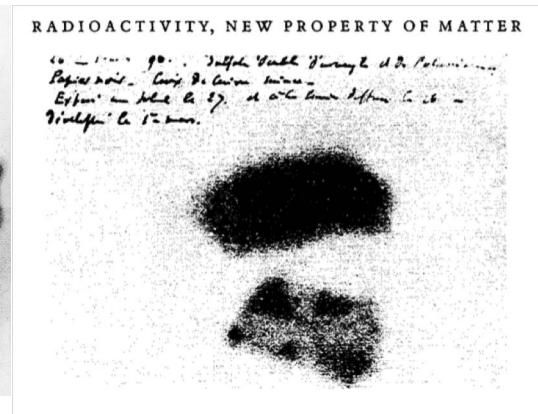
# Particle Detectors

# HISTORY

# First Detectors

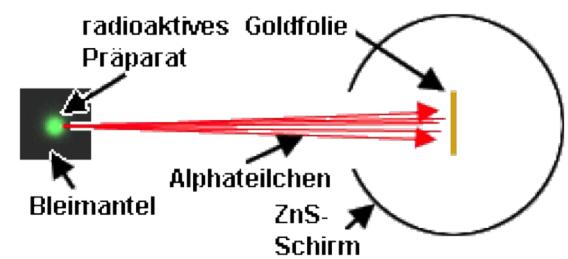
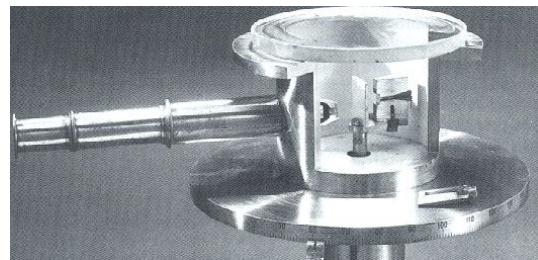
## Photographic plates:

- X-ray of W. Röntgen's wife hand
- Henri Bequerel's first “picture” of Uranium



## Rutherford's scattering experiment:

- Measurement of scattered atoms by looking to scintillation light of ZnS



# Forschung in Wien

1910: *Institut für Radiumforschung*  
der kaiserlichen **Akademie der  
Wissenschaften** in Wien gegründet  
(1090 Wien, Boltzmanngasse 3)

- Weltweit erstes Institut zur Erforschung der Radioaktivität
- Pechblende aus St. Joachimsthal
- Erster Direktor **Stefan Meyer**, Assistent **Victor Hess**
- Später *Institut für Mittelenergiephysik*, heute *Stefan Meyer Institut für subatomare Physik*



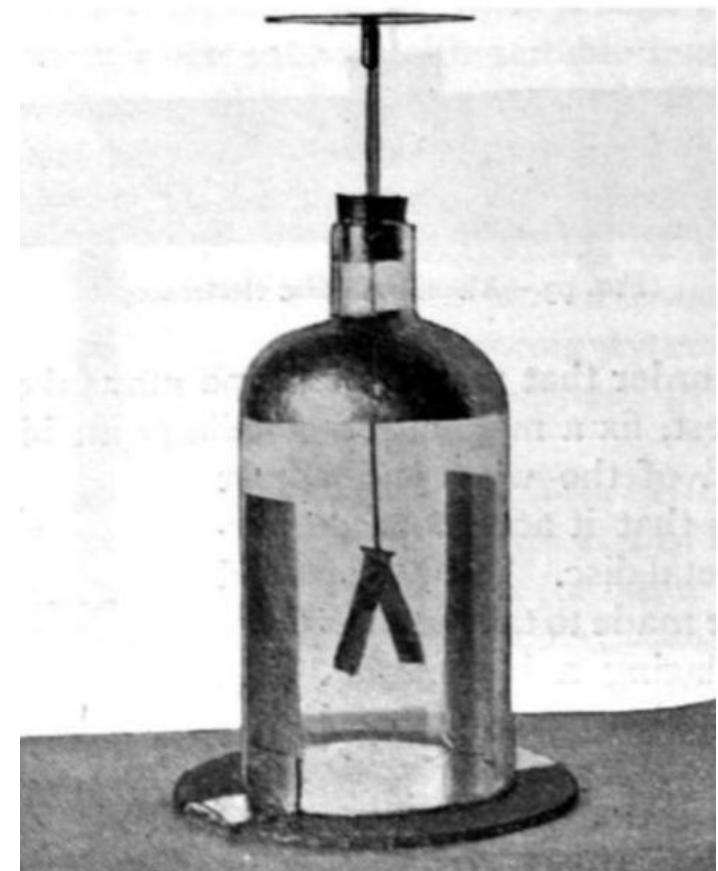
# Victor Franz Hess

- Physikstudium in Graz
  - 1906 Promotion  
*Sub auspiciis Imperatoris*
- Habilitation an Universität Wien  
1906-1910 über die  
*„Absolutbestimmung des Gehalts  
der Atmosphäre an  
Radiuminduktion“*
- Beginn am Institut für  
Radiumforschung 1910
  - Forschung über Luftionisierung unter  
Stefan Mayer



# Warum ist Luft leitfähig?

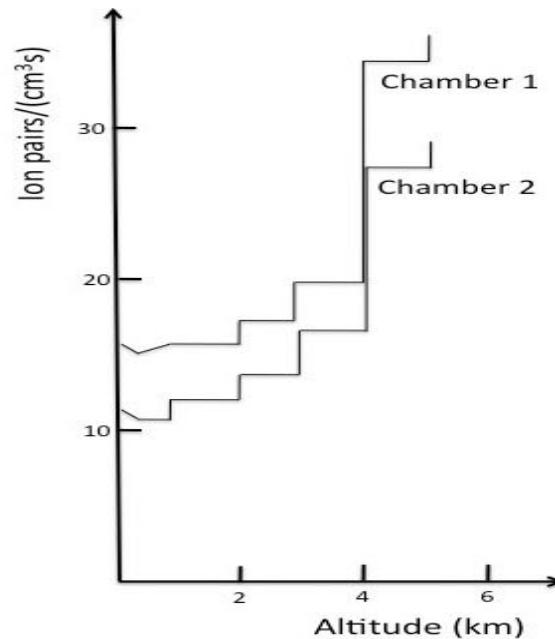
- Anfang 20. Jahrhundert:  
Frage nach “Elektrisierung”  
(Ionisation) der Luft
- Horizontale Messung  
(Uranquelle -> Detektor) durch  
natürliche Radioaktivität  
gestört
  - Abnahme in steigenden Höhen
- Abhilfen:
  - Experimente am Eiffelturm  
(Höhenunterschied)
  - Ballonfahrt



Elektrometer zur Messung der Ionisation

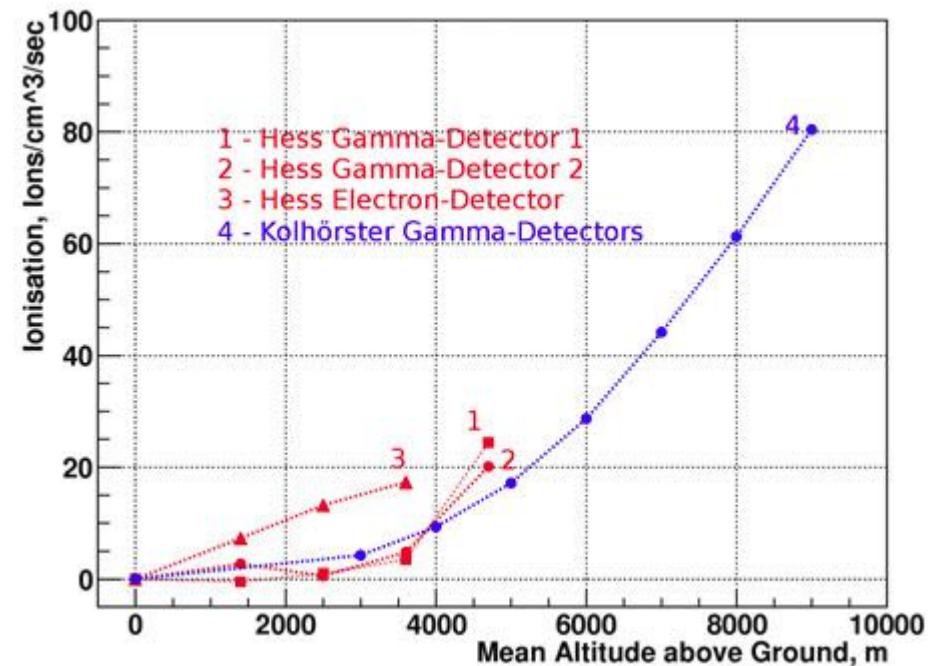
# Messung der “Luftionisation”

Viktor F. Hess (Wien), Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten.

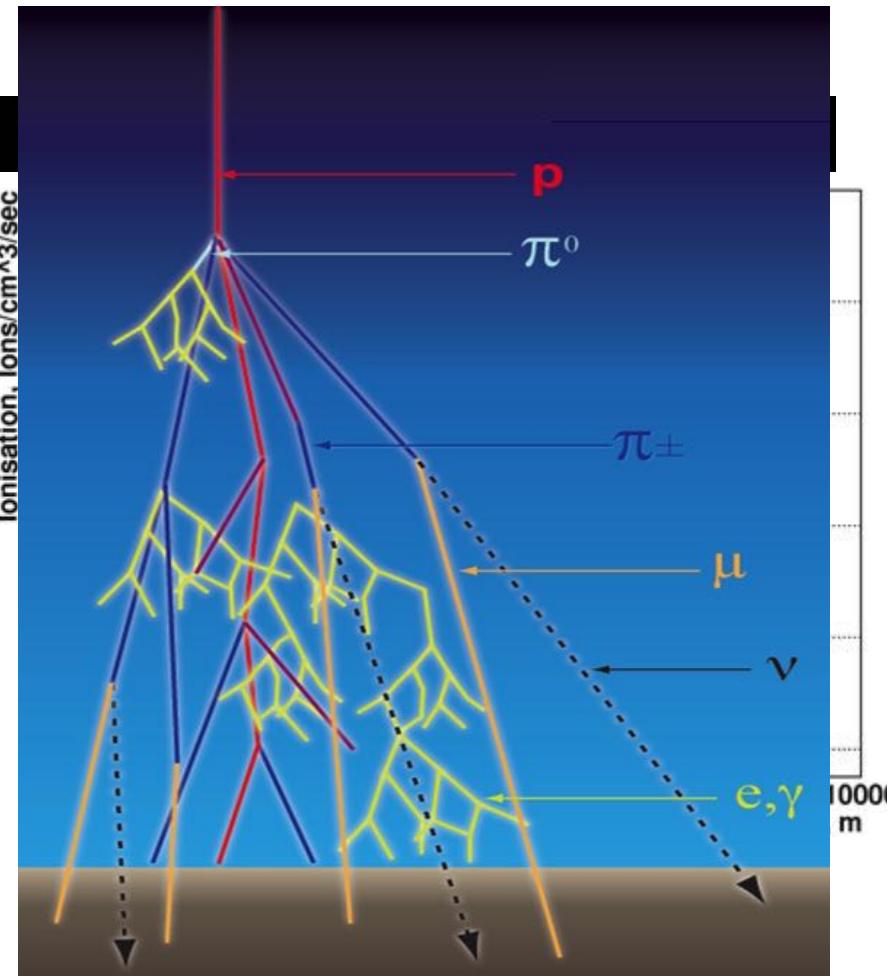


Physikalischen Zeitschrift 13 (1912), 1084.

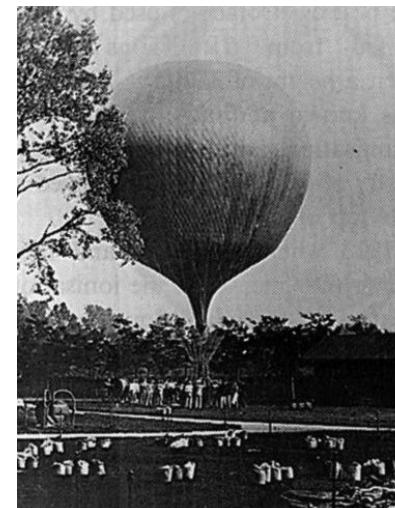
Bestätigung durch Werner Kolhörster 1913:



# Kosmische Strahlung



- Die Kosmische Strahlung bombardiert die Erde ständig mit Teilchen
- Entdeckung der sogenannten „Höhenstrahlung“ durch Viktor Hess 1912 (Physik-Nobelpreis 1936)

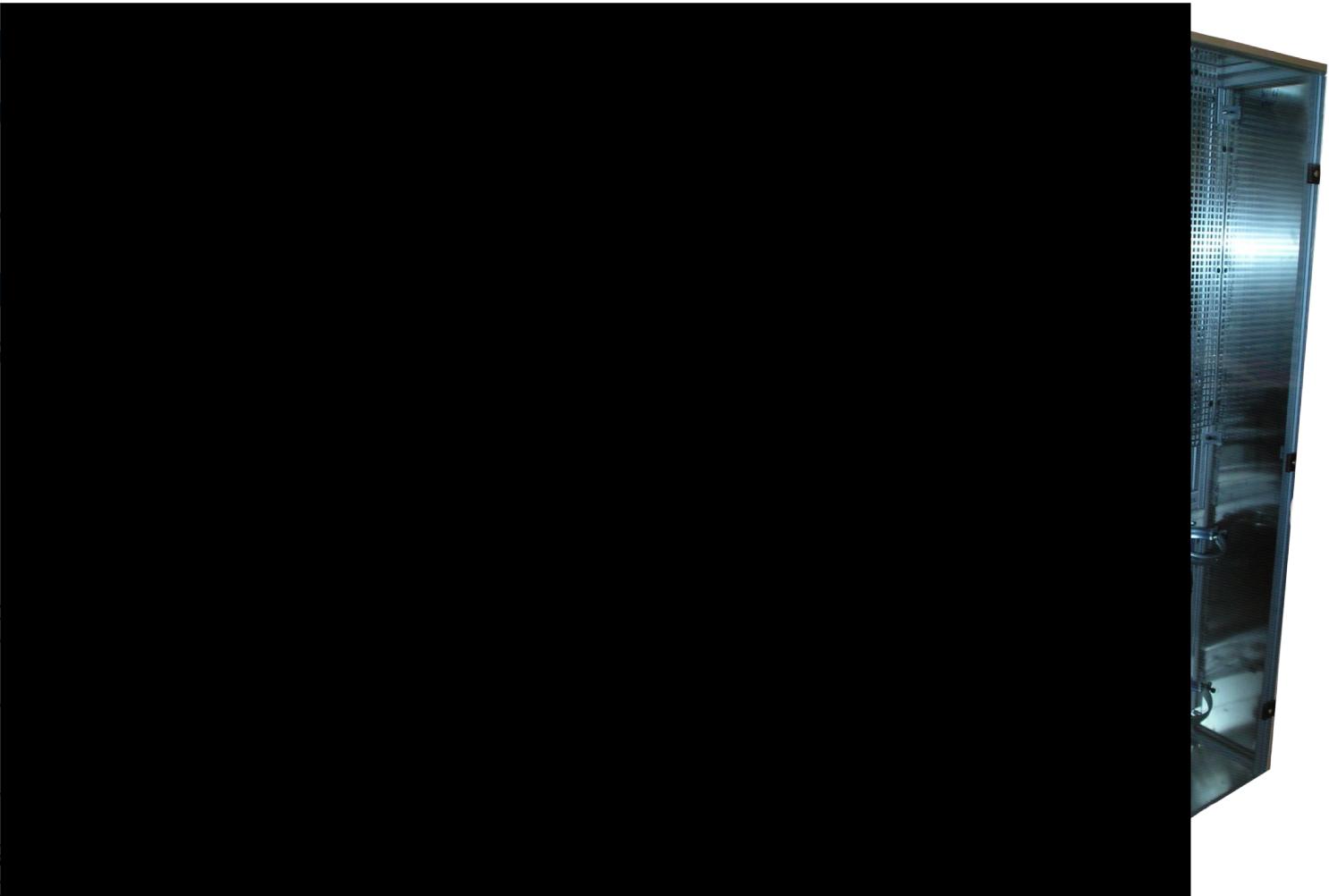
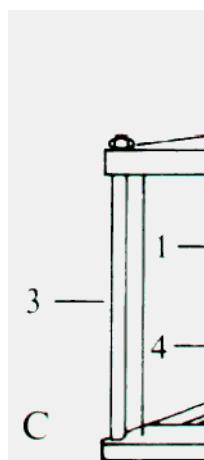


# Funkenkammer

- Macht  
– Ha

## Funktion

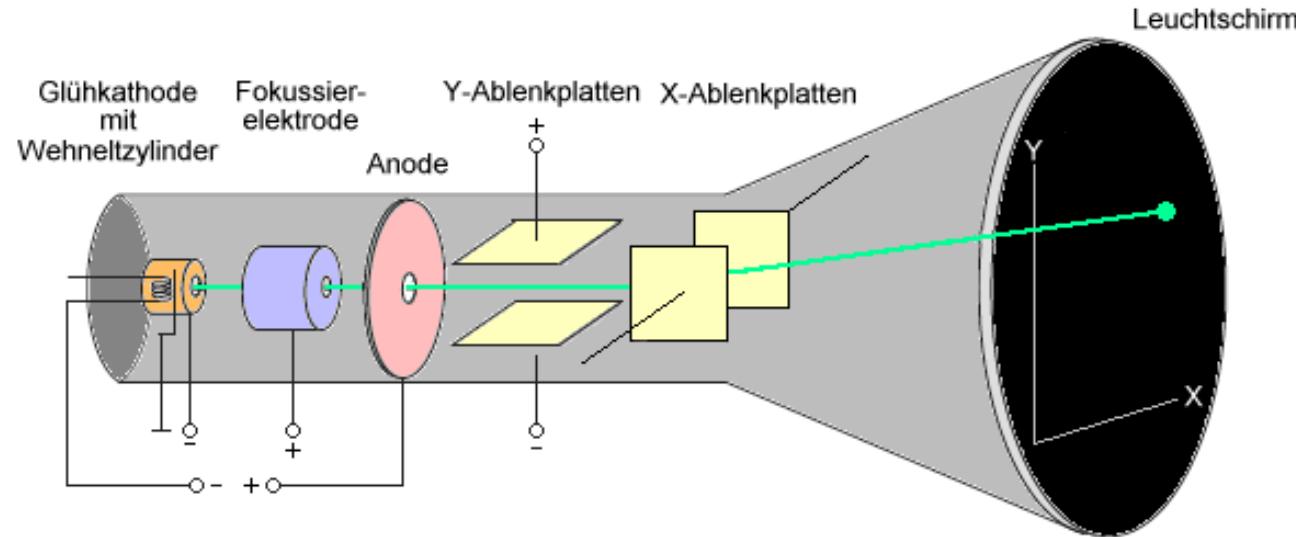
- Hoch  
zwis
- Myo



Domestizierung Kosmischer Strahlung

# TEILCHENBESCHLEUNIGER

# Der einfachste Beschleuniger



Ein Röhrenfernseher ist der einfachste  
**elektrostatische Beschleuniger:**

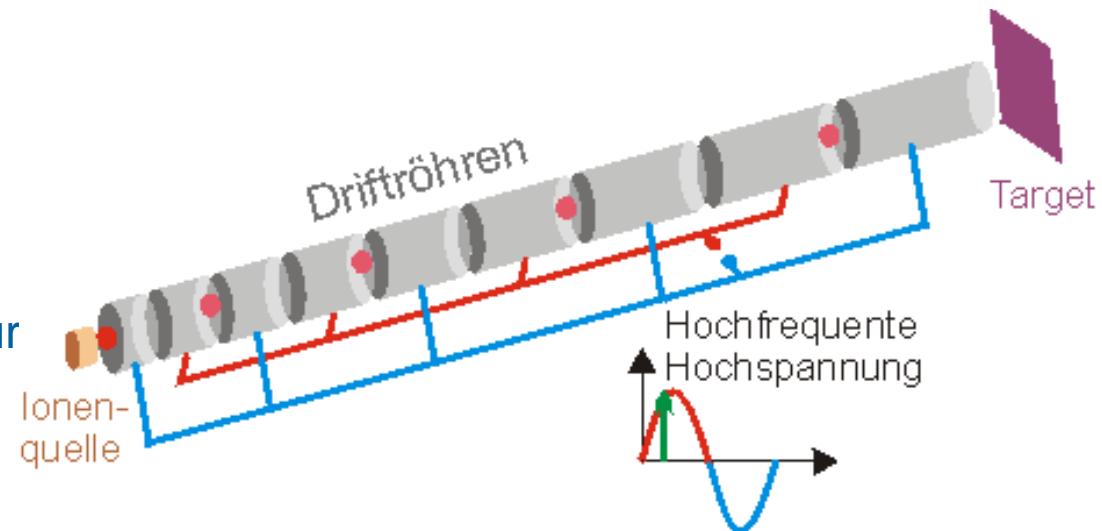
- Erzeugung von freien Elektronen mittels Glühkathode
- Beschleunigung mittels Hochspannung
- Ablenkung mittels magnetischer Felder



# Zwei prinzipielle Arten von Beschleunigern

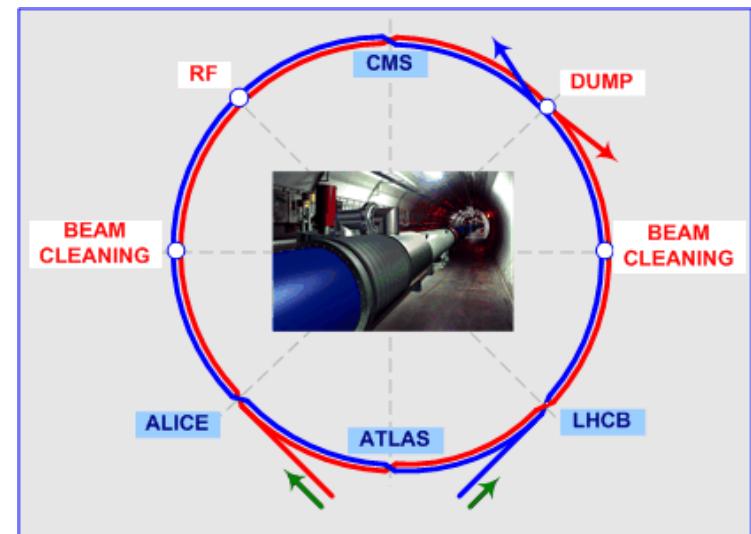
- **Linearbeschleuniger:**

- Weiterentwicklung eines elektrostatischen Beschleunigers
- Nachteil: Teilchen stehen nur einmal zur Beschleunigung zur Verfügung.

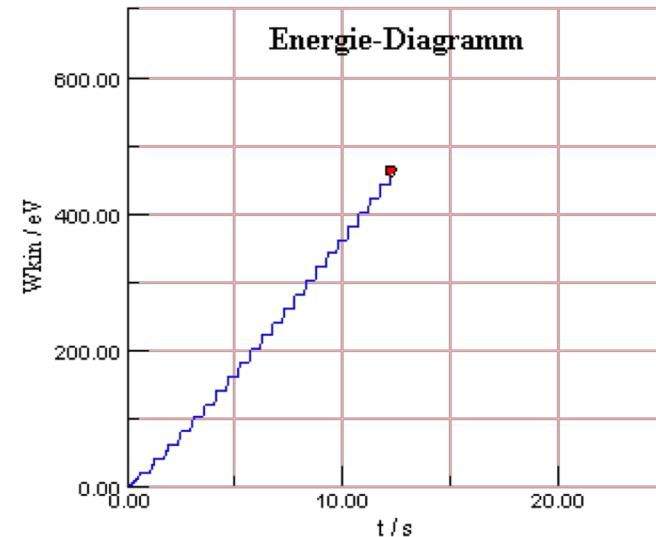
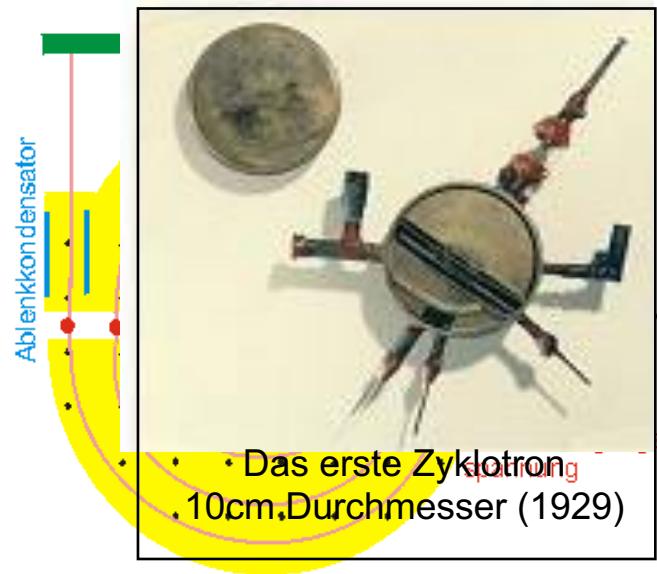


- **Ringbeschleuniger:**

- Synchrotron
- Vorteil: ringförmig :-) Teilchen fliegen immer und immer im Kreis
- Oft zwei Beschleuniger gegenläufig
- Man benötigt mehr Komponenten, um Teilchen auf Kreisbahn zu halten



# Zyklotron



- Beschleunigung durch das el. Feld zwischen den Dees
- Halbkreis durch Magnetfeld (Lorentzkraft) in den Dees

Umlaufdauer bei Annahme einer Kreisbahn

$$T = 2\pi \cdot \frac{m}{q \cdot B}$$

- Limit: ca. 10MeV bei Protonen
- Warum? Durch relativistische Effekte (Massenzunahme)

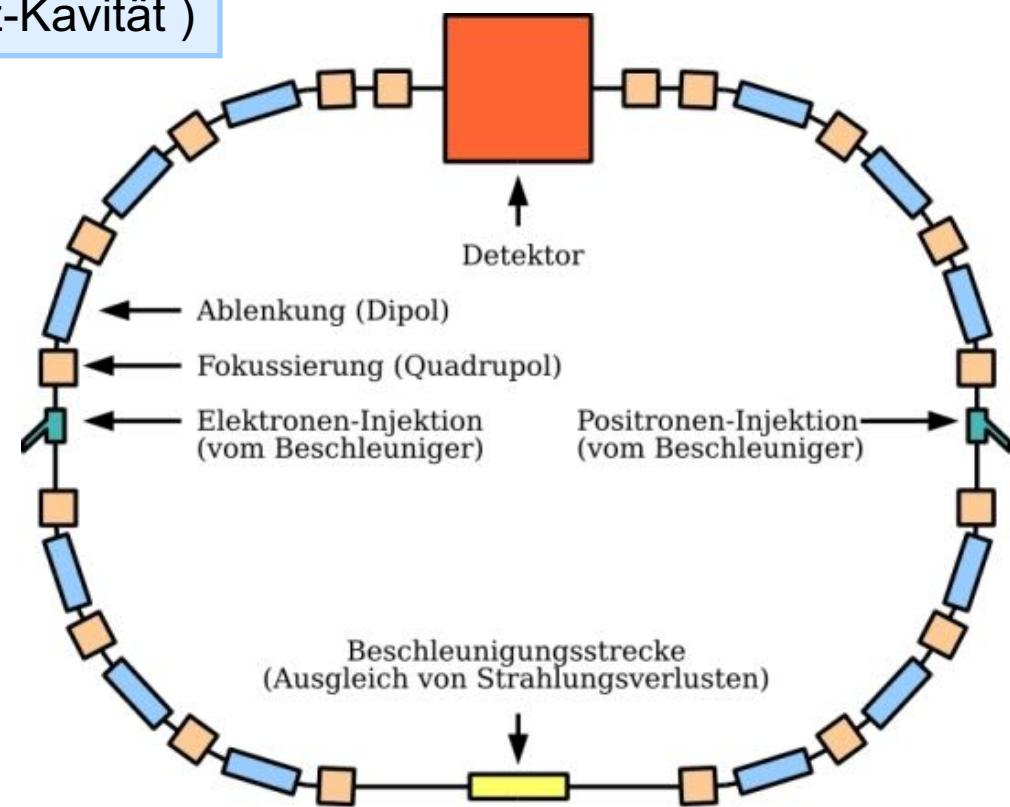
# Komponenten eines Synchrotron

- **Teilchen** (Elektronen oder Protonen)

- **Beschleunigung** (Hochfrequenz-Kavität )

Magnete zum  
• **Ablenken (Dipol)**  
• **Fokussieren (Quadrupol)**

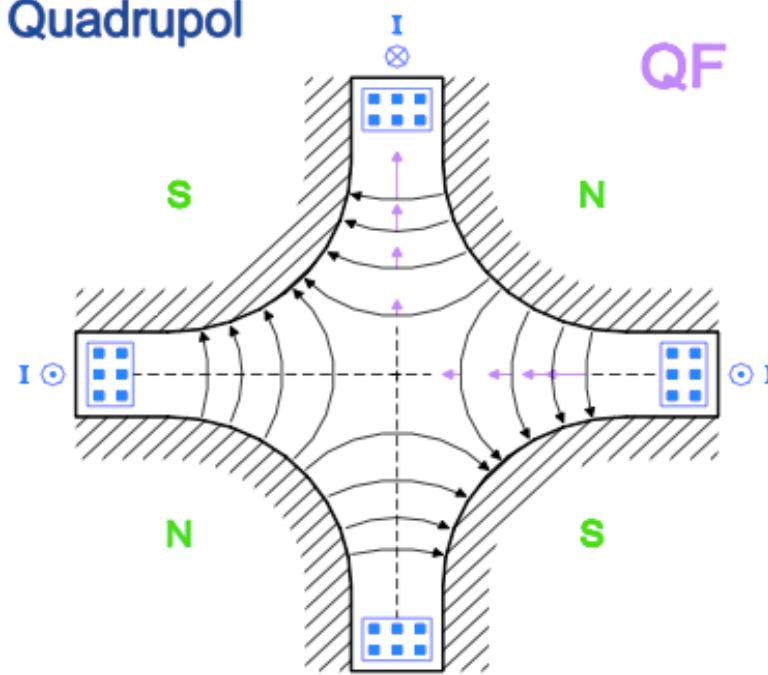
Ein oder mehrere  
**Detektoren** an den  
Kollisionspunkten



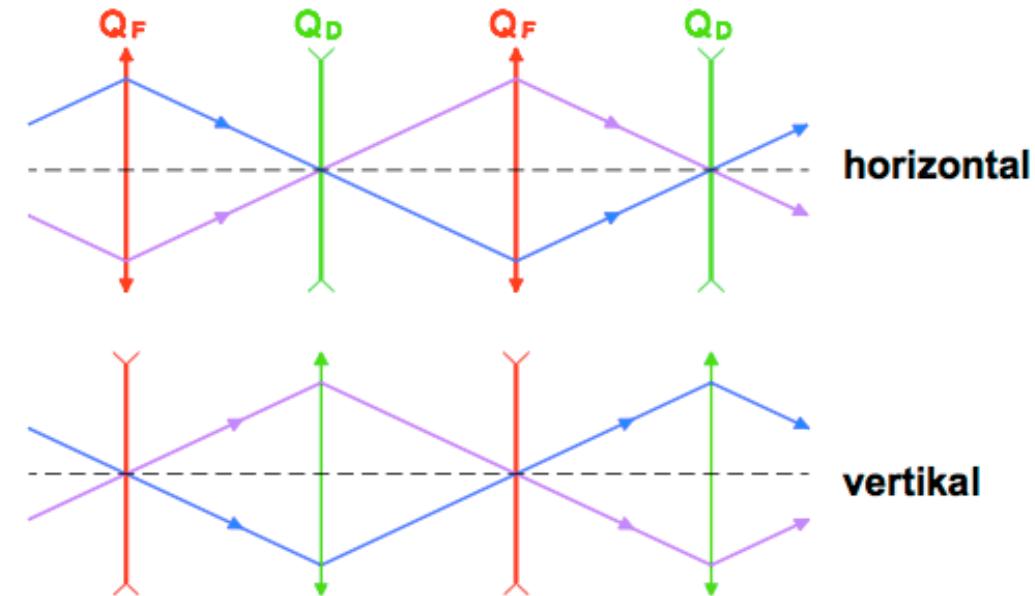
## Synchrotron verwenden Quadrupole

- meist zwei Quadrupolmagnete hintereinander angebracht, aber um  $90^\circ$  zueinander verdreht
- Analogon: fokussierende Linsen optischer Systeme

Quadrupol



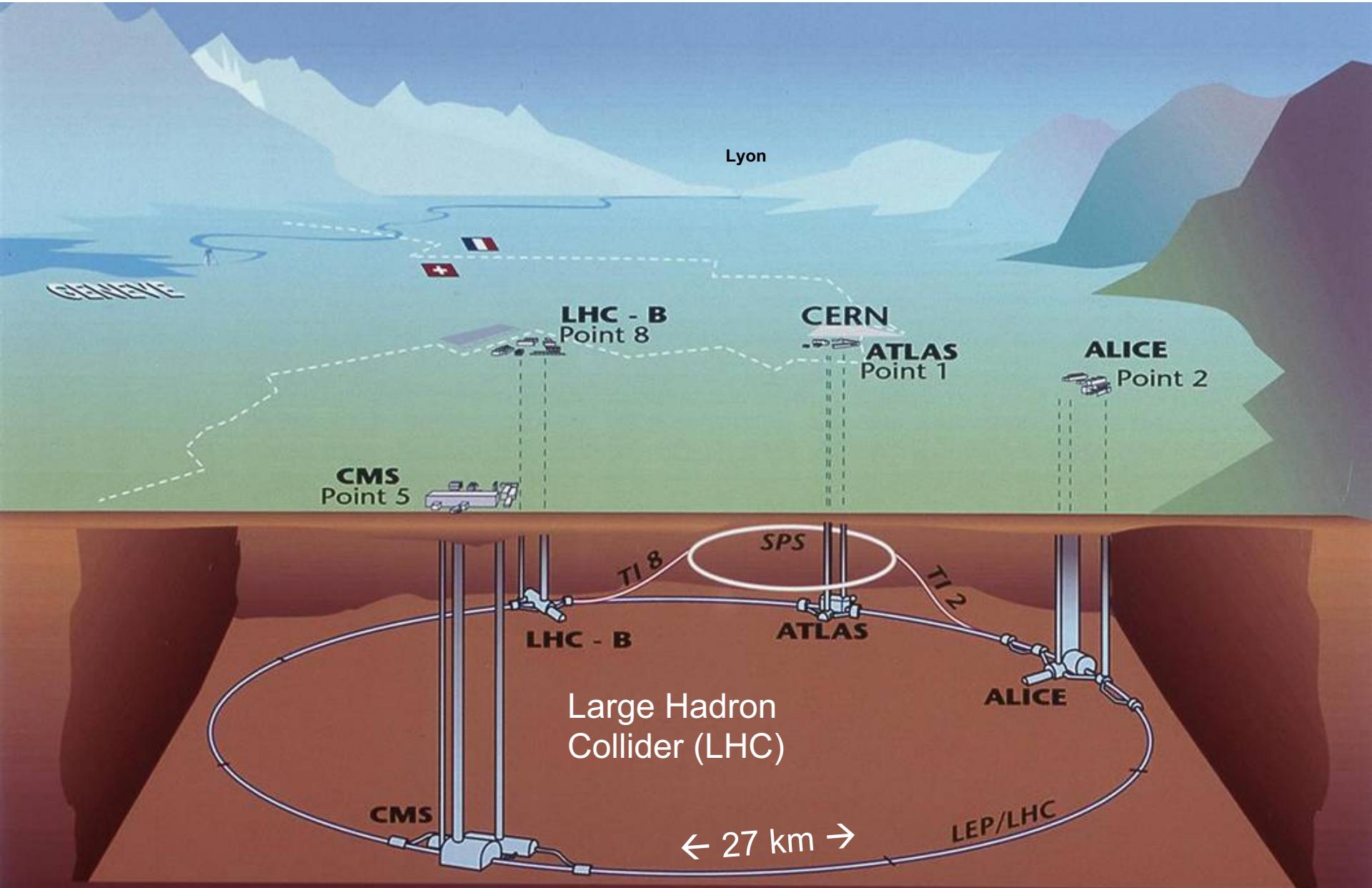
“Alternating gradient” Fokusierung



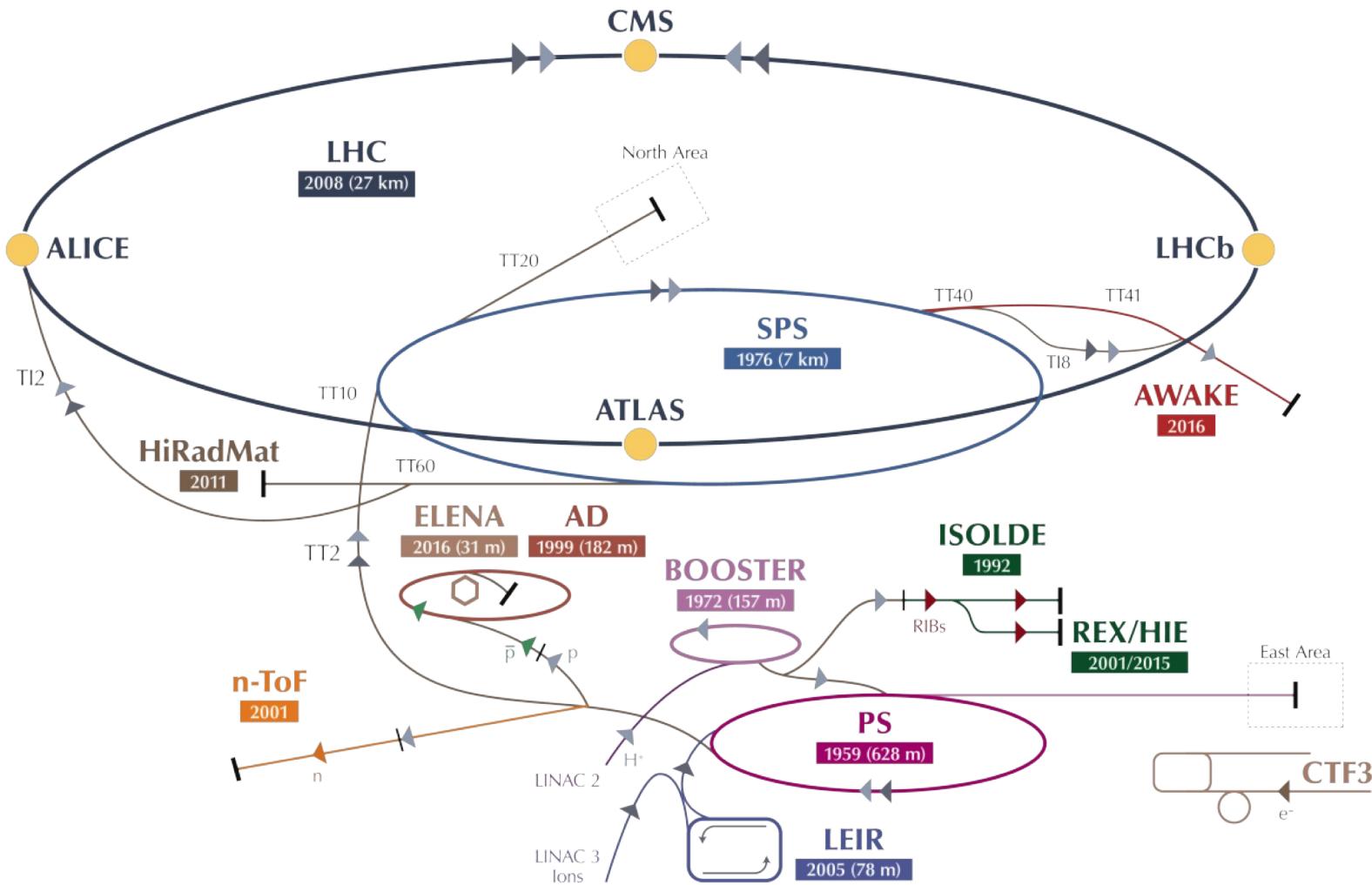
# LHC AblenkMagnete (Dipole)



- 15m Länge, 35t Masse
- 1232 Stück insgesamt
- Magnetfeld: 8.33 Tesla
- Betrieb mit flüssigem Helium (insgesamt 130t) bei 1.9K

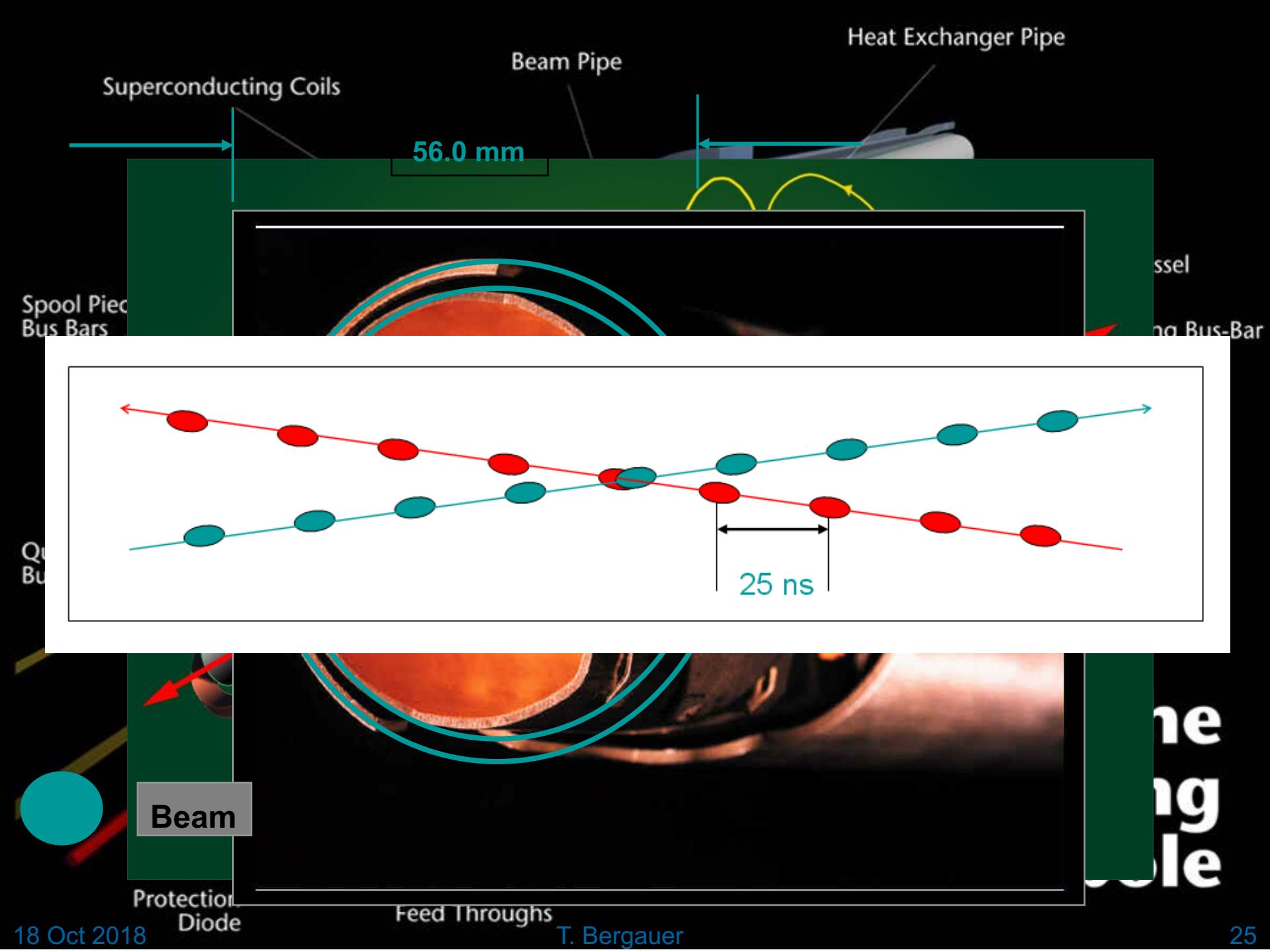


# Beschleunigerkomplex des CERN



# Ablauf der Beschleunigung



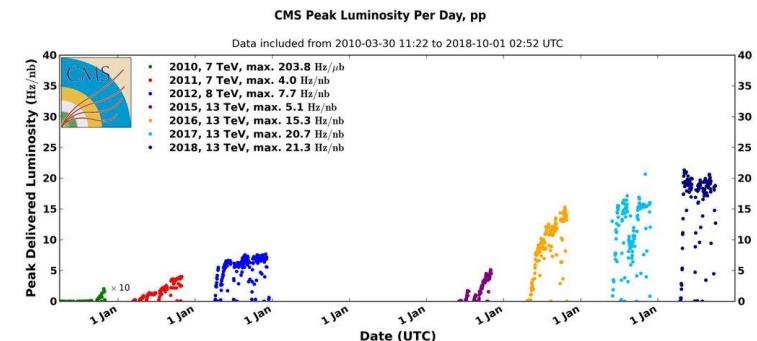


## Spontane Luminosität $L$ [ $\text{cm}^{-2}\text{s}^{-1}$ ]:

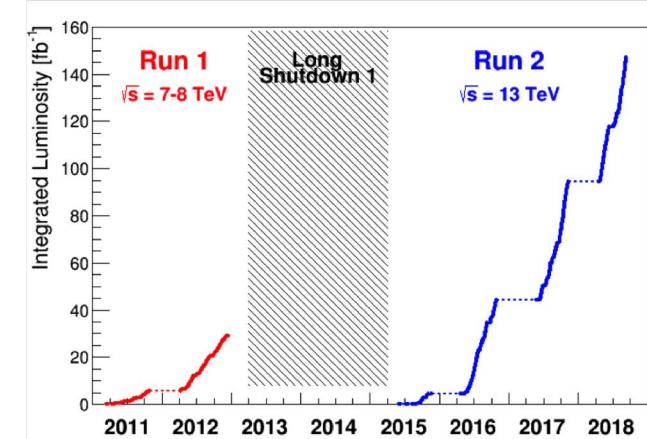
- Anzahl der Teilchenbegegnungen pro Zeit und Fläche

$$L = \frac{n \cdot N_1 \cdot N_2 \cdot f}{4\pi\sigma_x\sigma_y}.$$

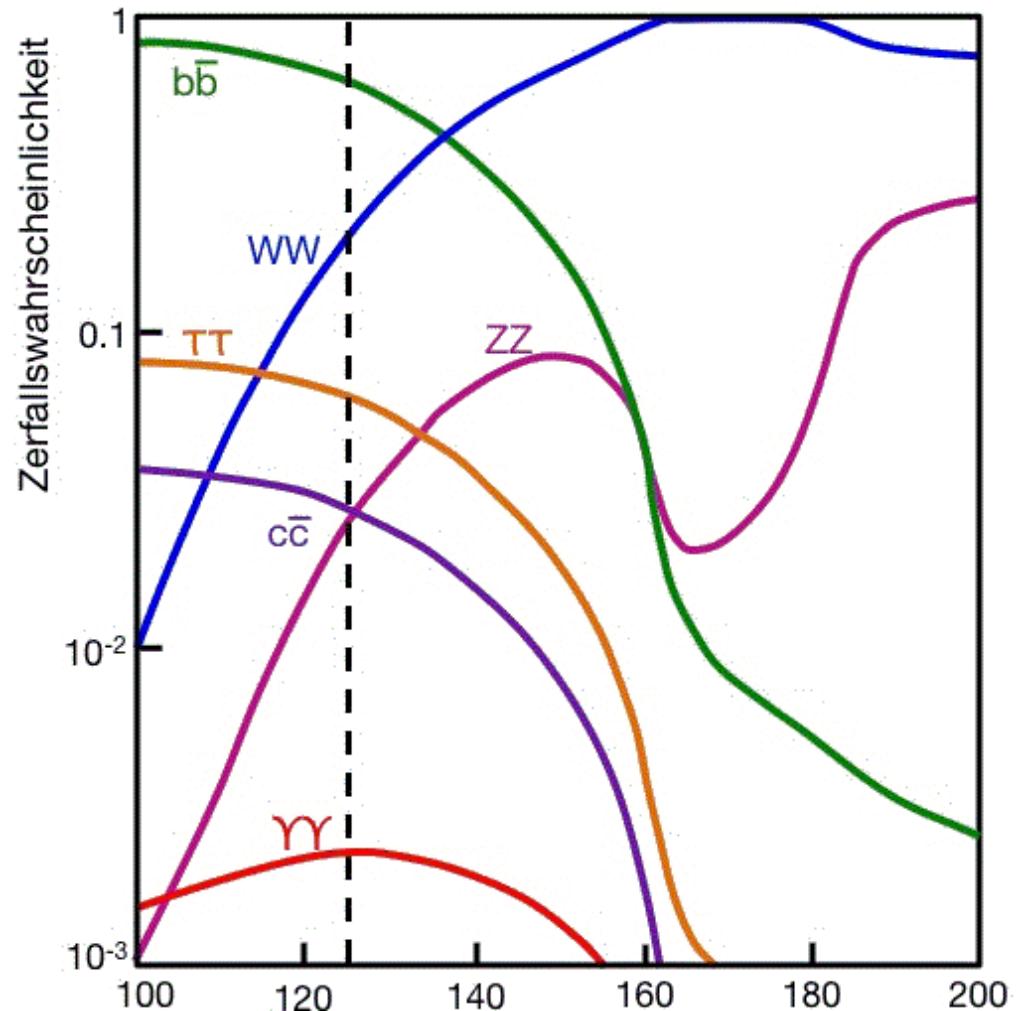
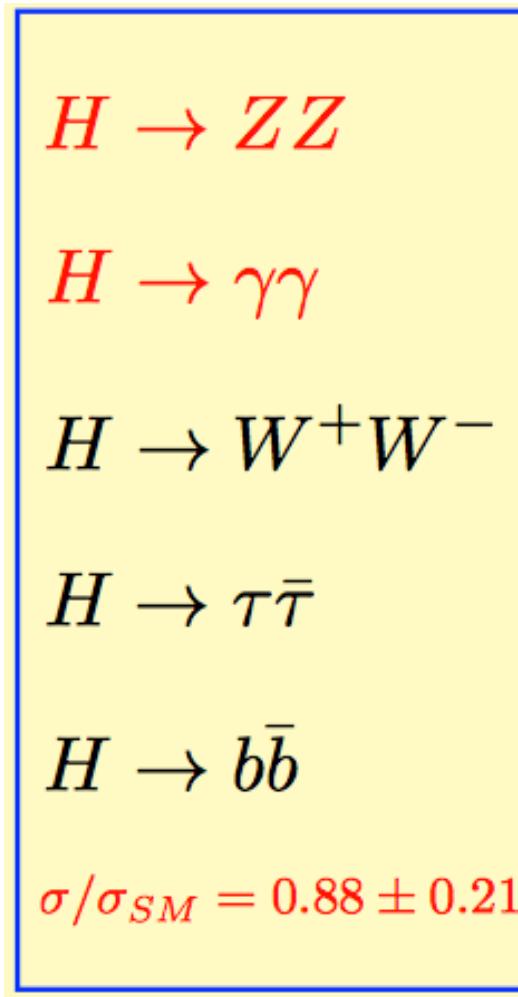
- Ereignisrate  $R = \sigma * L$



- ## Integrierte Luminosität [ $\text{fb}^{-1}$ ]
- Totale Anzahl der Kollisionen



## Higgs Branching Ratios

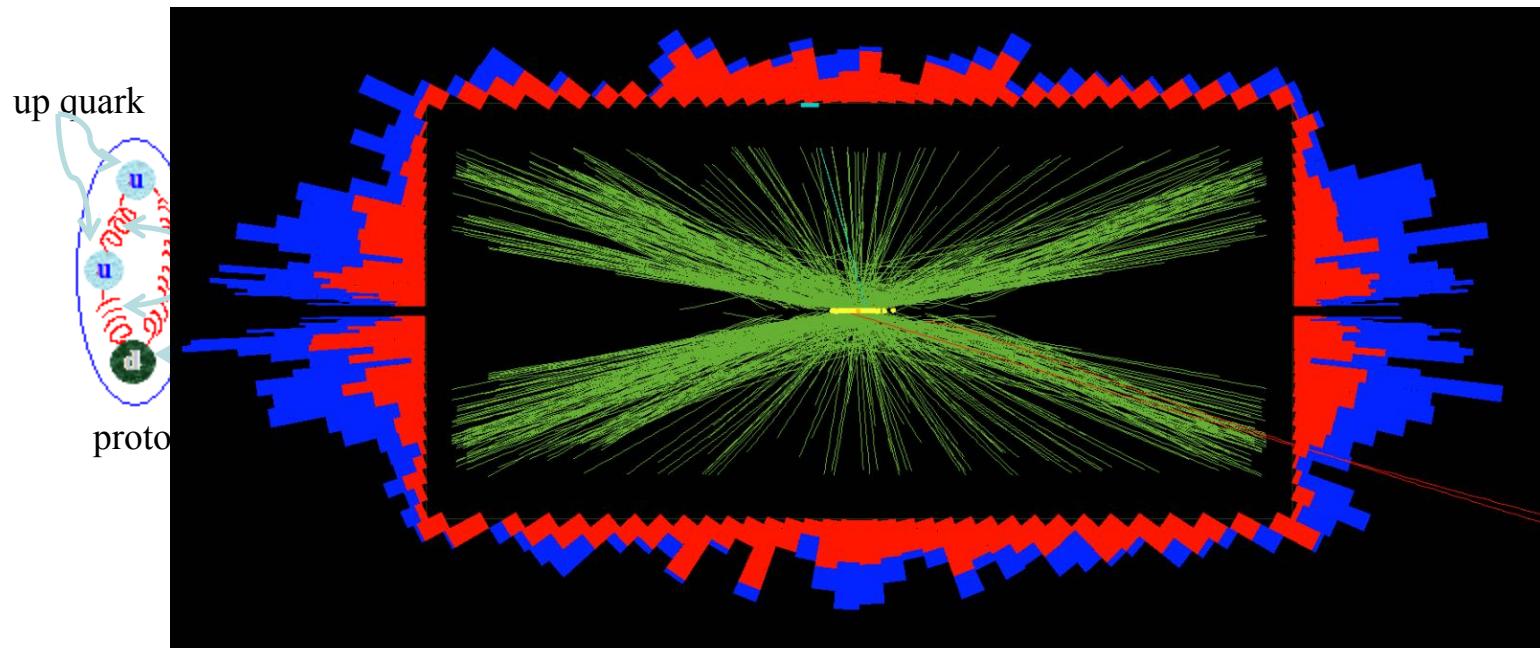


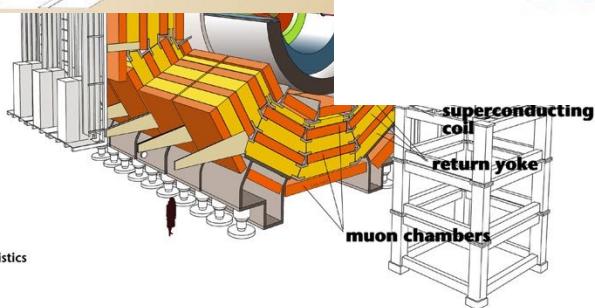
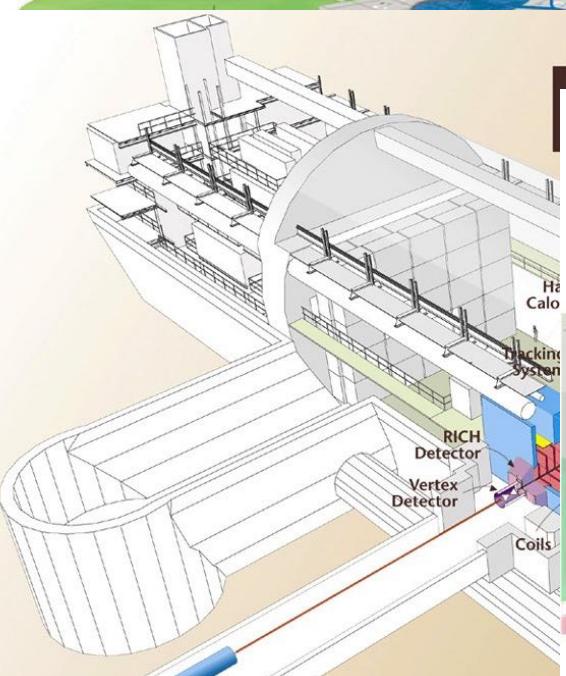
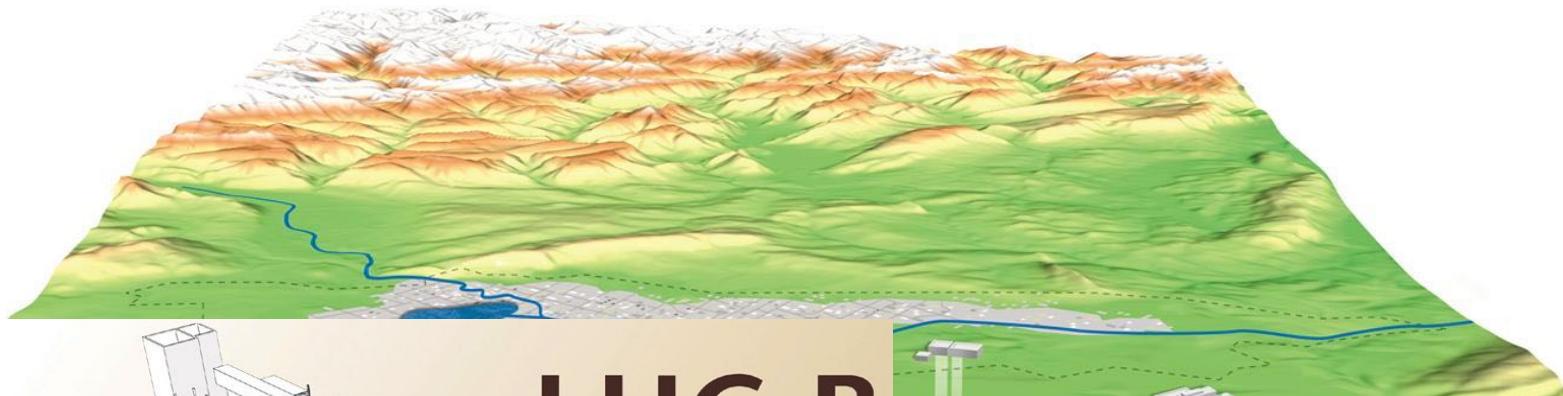
# Teilchendetektoren Kollisionen? oder “Die Experimente”



# Kollisionen

- Die Protonen haben 99.99999% der Lichtgeschwindigkeit und eine kinetische Energie (Bewegungsenergie) von 7 TeV.
- **40 Millionen mal pro Sekunde** treffen zwei Wolken, jede gefüllt mit **jeweils 100 Milliarden Protonen** aufeinander
- Dabei kollidieren rund **10 bis 20 Protonen** miteinander

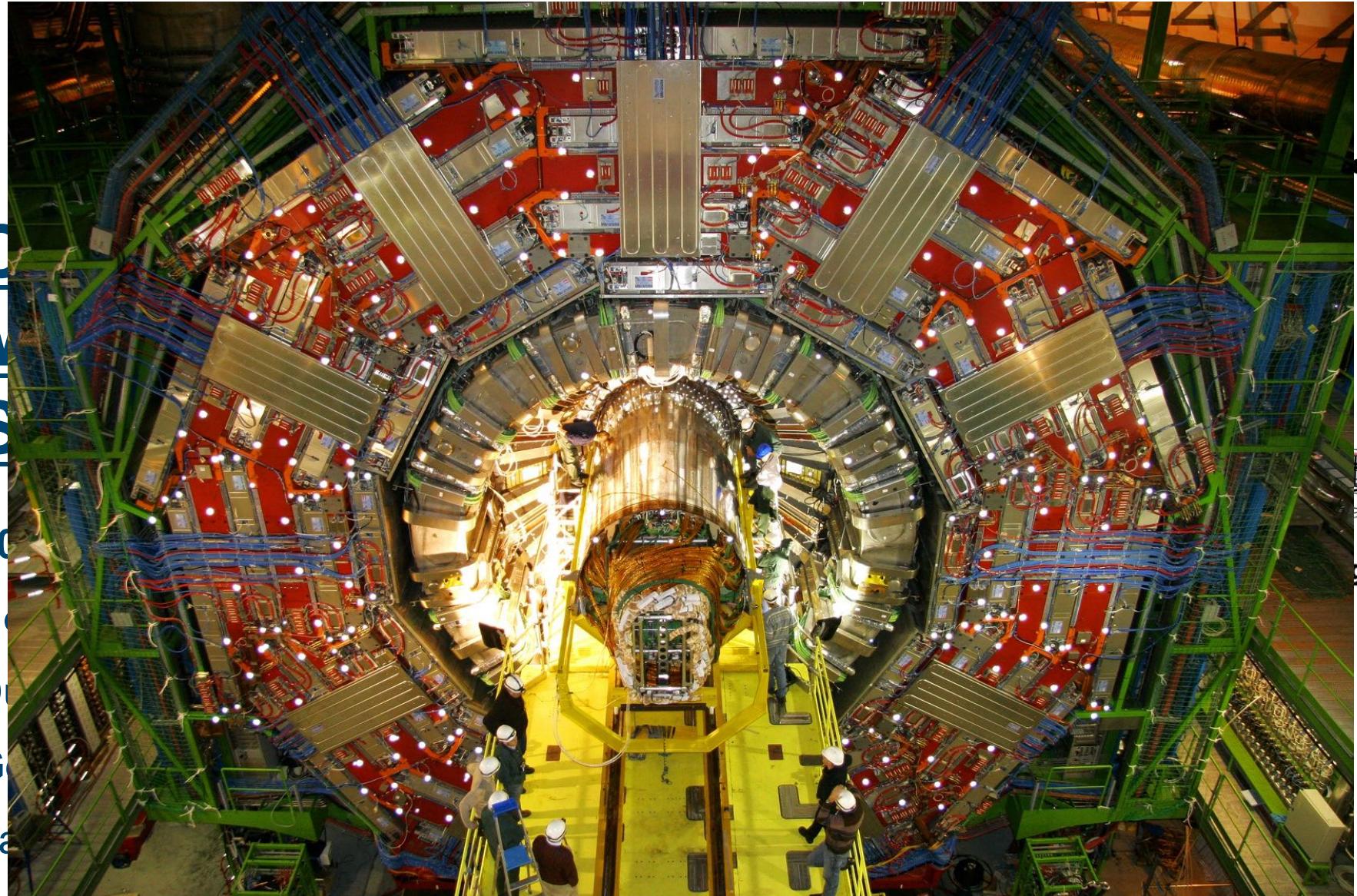


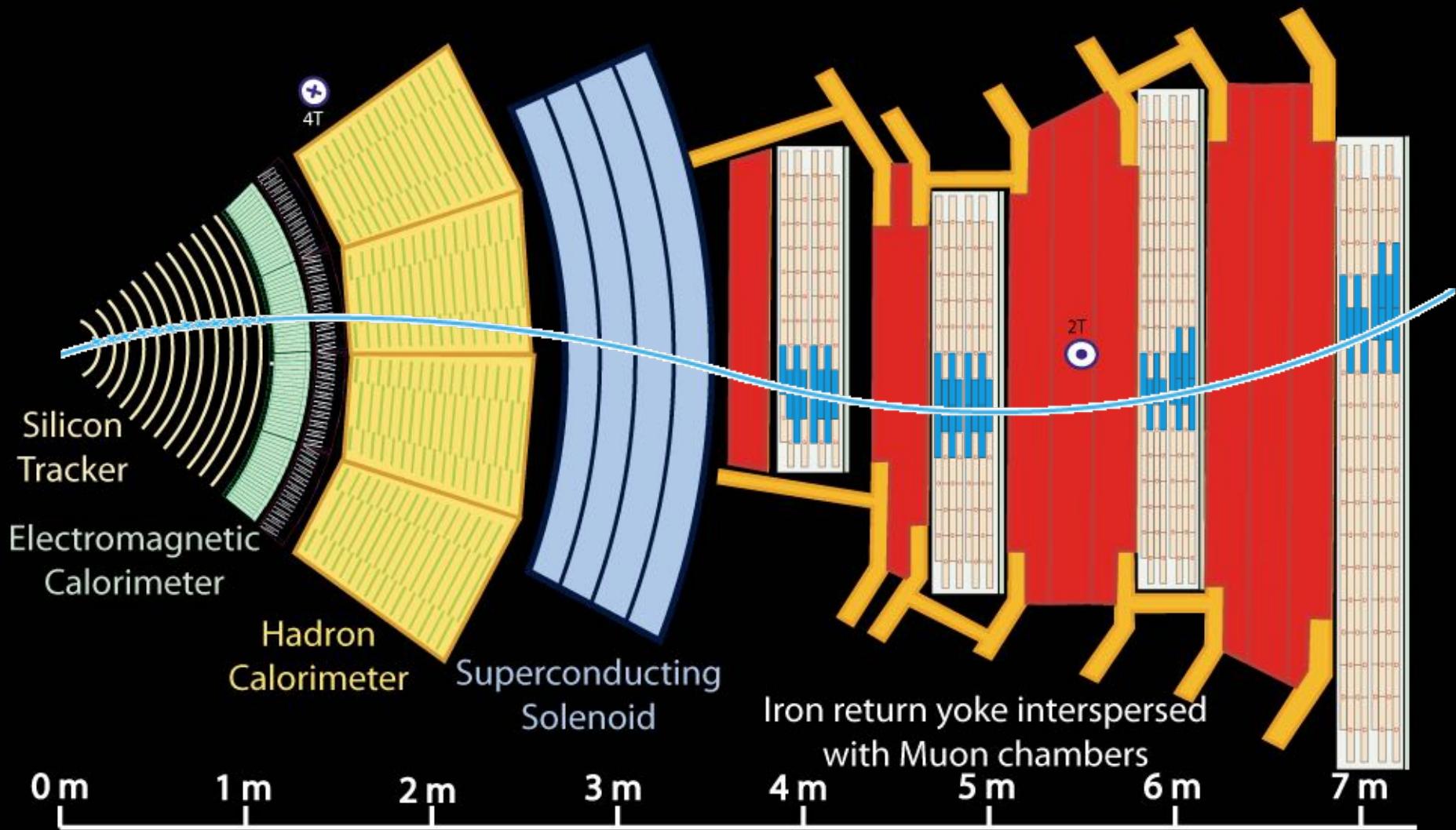


#### Detector characteristics

Width: 22m  
Diameter: 15m  
Weight: 14'500t

C  
M  
S  
10  
H  
D  
G  
(fa





Key:

— Muon

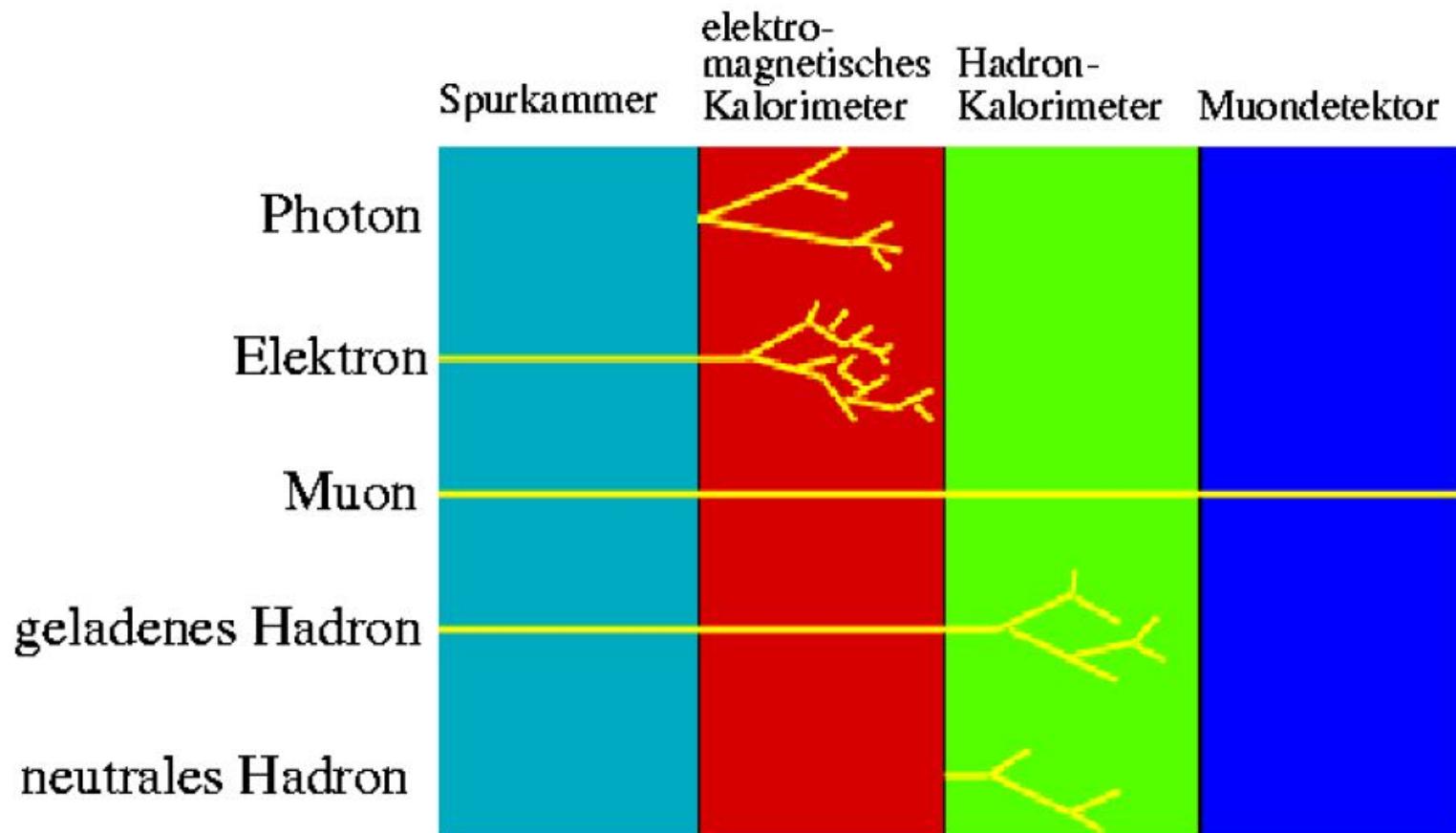
— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

----- Photon

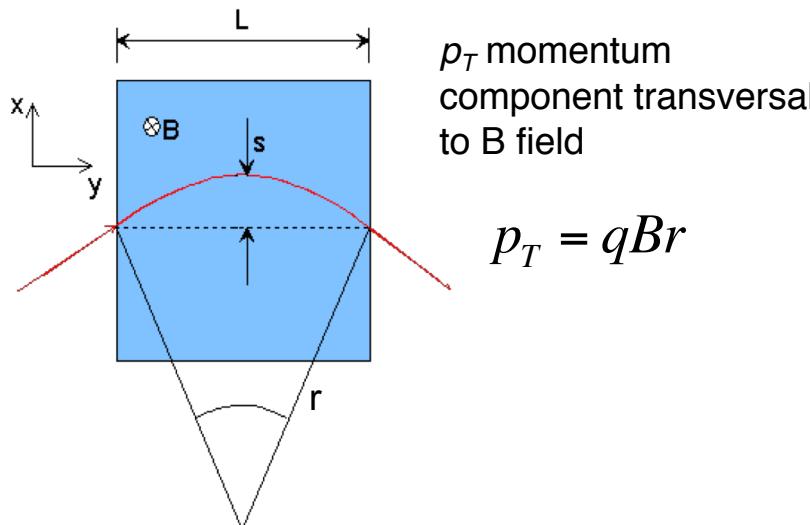
# Prinzipieller Aufbau eines Experiments



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# Realistic possibilities for determining particle properties

- Momentum  $p$  of charged particles: determination of the radius of curvature within magnetic field



- Particle charge (sign): from deflection (left –right) within magnetic field

- Velocity  $v$ : time of flight measurement, RICH, etc.
- Life time  $\tau$ : measurement of the decay length
- Energy  $E$ : full absorption in a calorimeter
- Mass  $m$ : calculation from momentum  $p$  and energy  $E$  or velocity  $v$

$$E^2 = m^2 c^4 + p^2 c^2$$

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

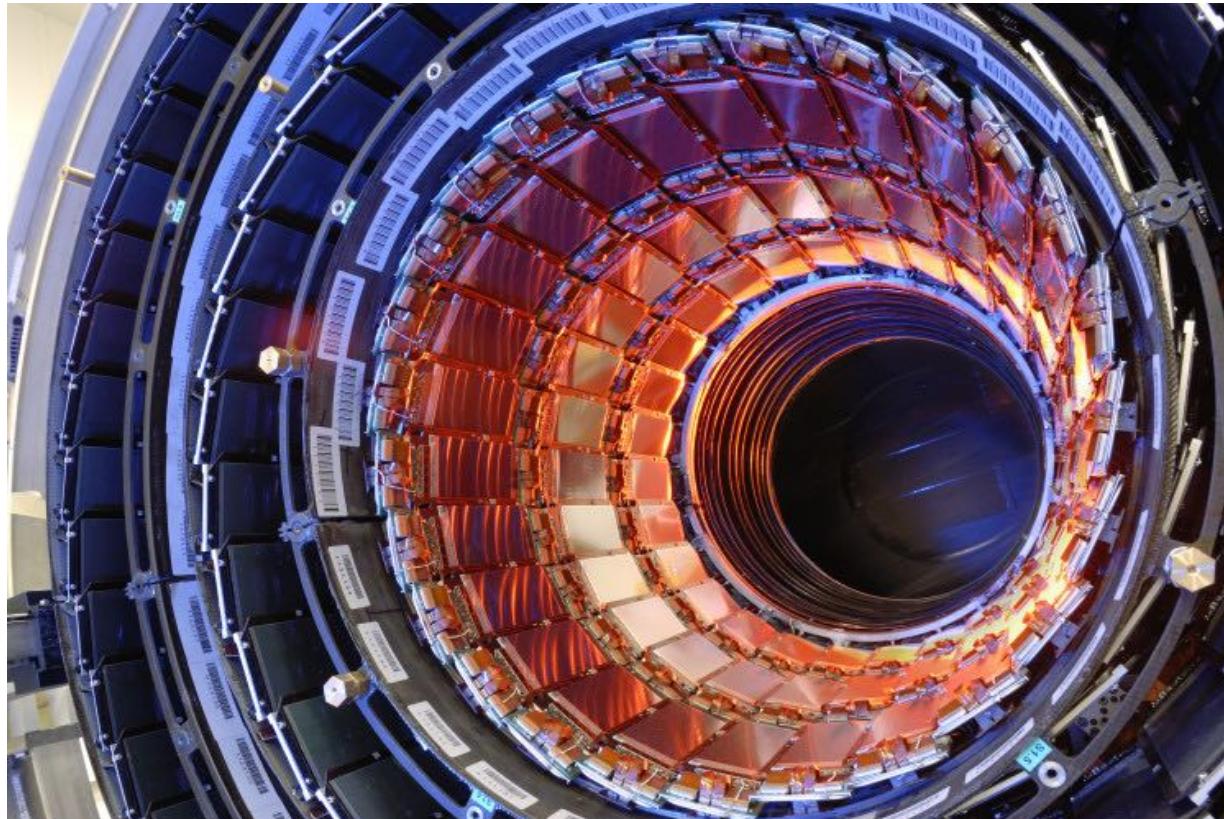
# Measurement Principles

A measurement requires an interaction of the particle with the material of the detector. The interaction provokes two effects:

- 1<sup>st</sup> **Creation of a detectable signal** (e.g. ionization → charges, excitation → scintillation, excitation of phonons → heat, etc.)  
That's what the detector is for!
  
- 2<sup>nd</sup> **Alteration of the particles properties** (energy loss, change of trajectory due to scattering, absorption)  
Unwanted side effects. They need to be as small as possible and well understood.

# Spurkammer – Der “Tracker”

Im innersten Teil eines solchen Detektors verwendet man meist eine Art “Digitalkamera”:



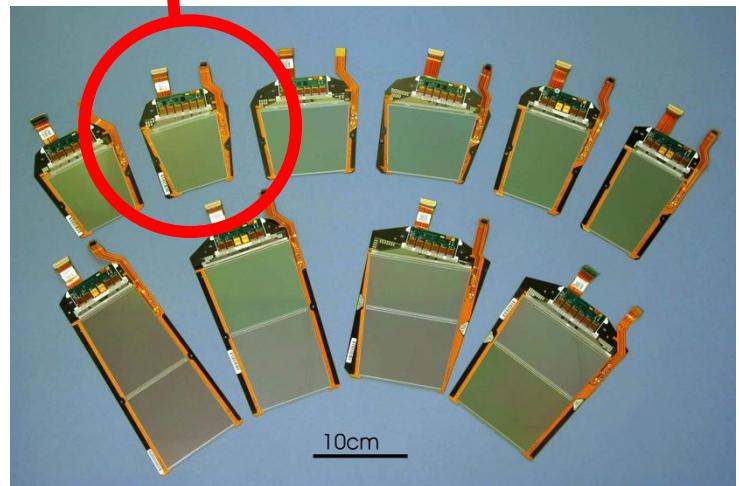
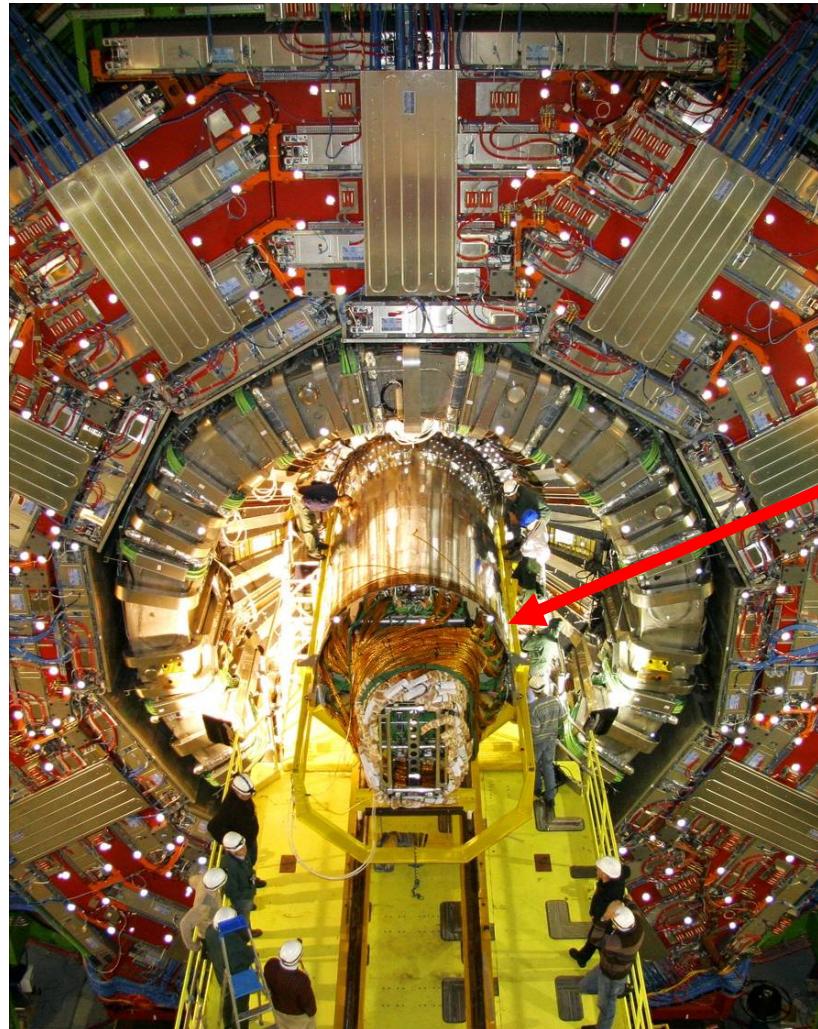
## Digitalkamera:

- Typisch  $2 \times 3 \text{ cm}^2$  Chipgröße in Spiegelreflexkamera
- 3-5 Fotos pro Sekunde

## CMS Tracker:

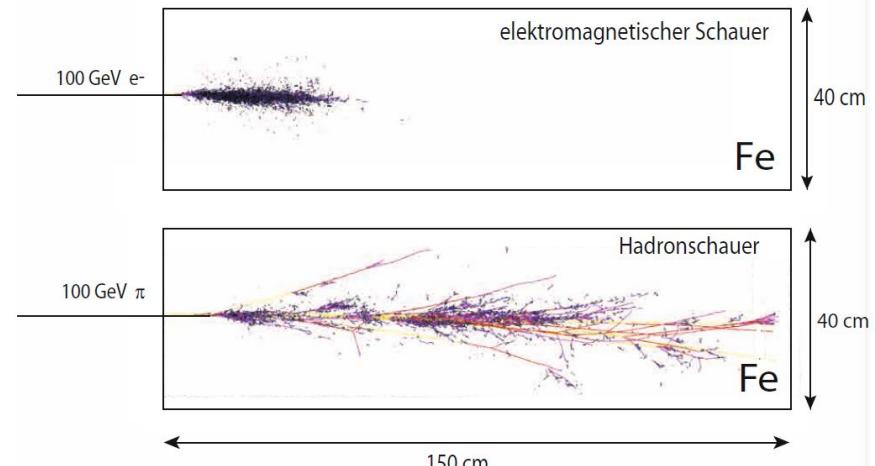
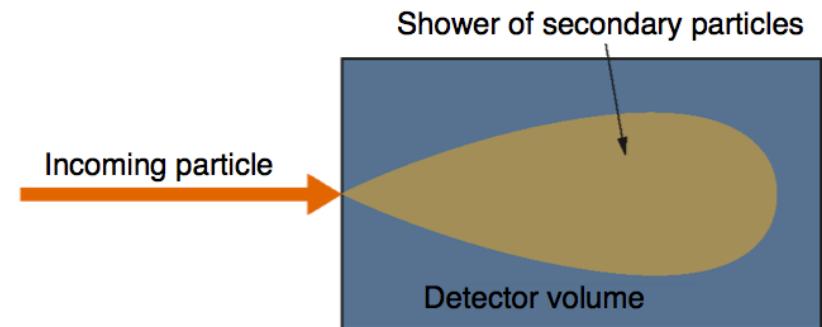
- $200 \text{ m}^2$  Detektorfläche
- 40 Millionen 3D-„Fotos“ pro Sekunde

# Bau des CMS Trackers





- fully absorbs the particles.
- Produced signals are measure for the energy of the particle.
- The particle initiates a particle shower. Each secondary particle deposits energy and produces further particles until the full energy is absorbed.

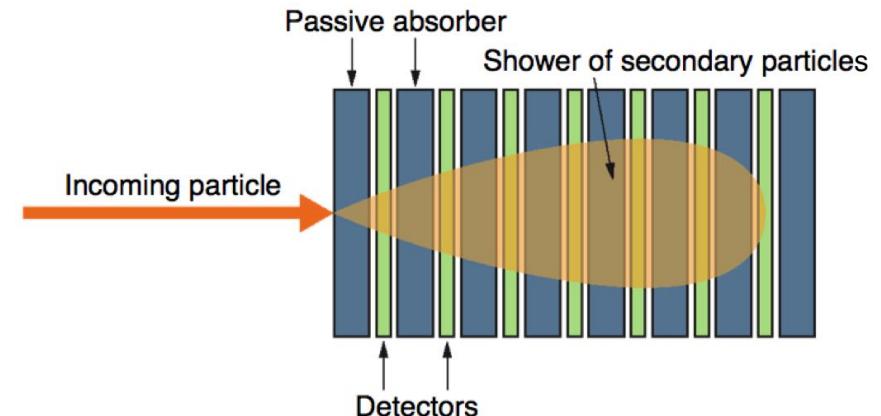


## homogenous calorimeter

- detector material is at the same time the absorbing material
- Best possible energy resolution achievable

## Sampling calorimeter

- Sandwich of passive absorber (lead, iron, copper,...)
- Active detectors (scintillators, Silicon)



- Bremsstrahlung and pair production are considered

- Cross section

$$\sigma \propto Z^2$$

$$X_0 \propto 1/Z^2$$

- Critical Energy  $E_k$

- where energy loss by bremsstrahlung equal ionization

- Total length  $s=t^*X_0$

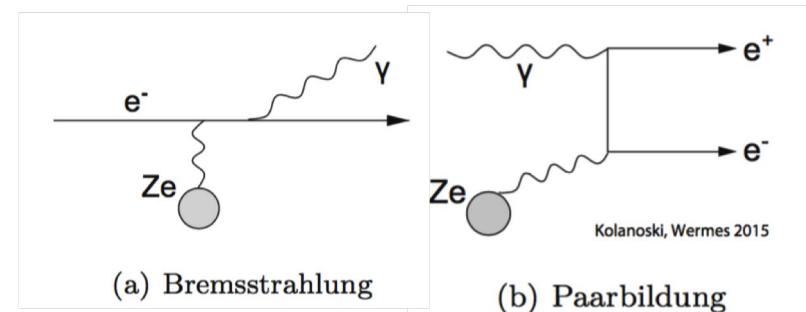
$$E = E_k = \frac{E_0}{2^{t_{max}}}$$

$$N_{max} = \frac{E_0}{E_k},$$

$$t_{max} = \frac{\ln E_0/E_k}{\ln 2}$$

**Message:**

- N scales linear with energy,
- $t_{max}$  logarithmic



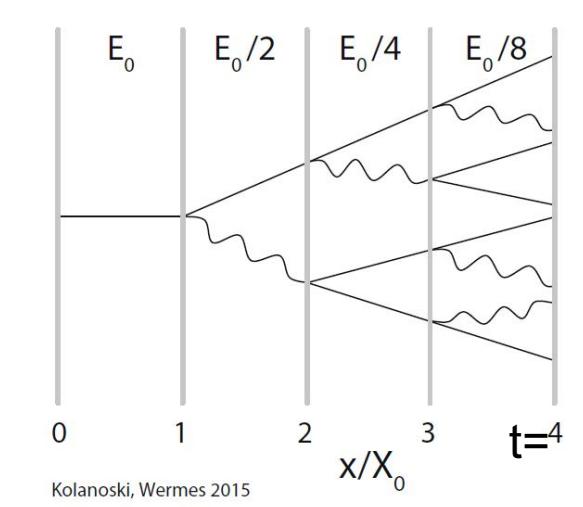
(a) Bremsstrahlung

(b) Paarbildung

Kolanoski, Wermes 2015

$$N = 2^t, \quad E = \frac{E_0}{2^t}$$

$$N_{tot} \approx \frac{E_0}{E_k},$$



Kolanoski, Wermes 2015

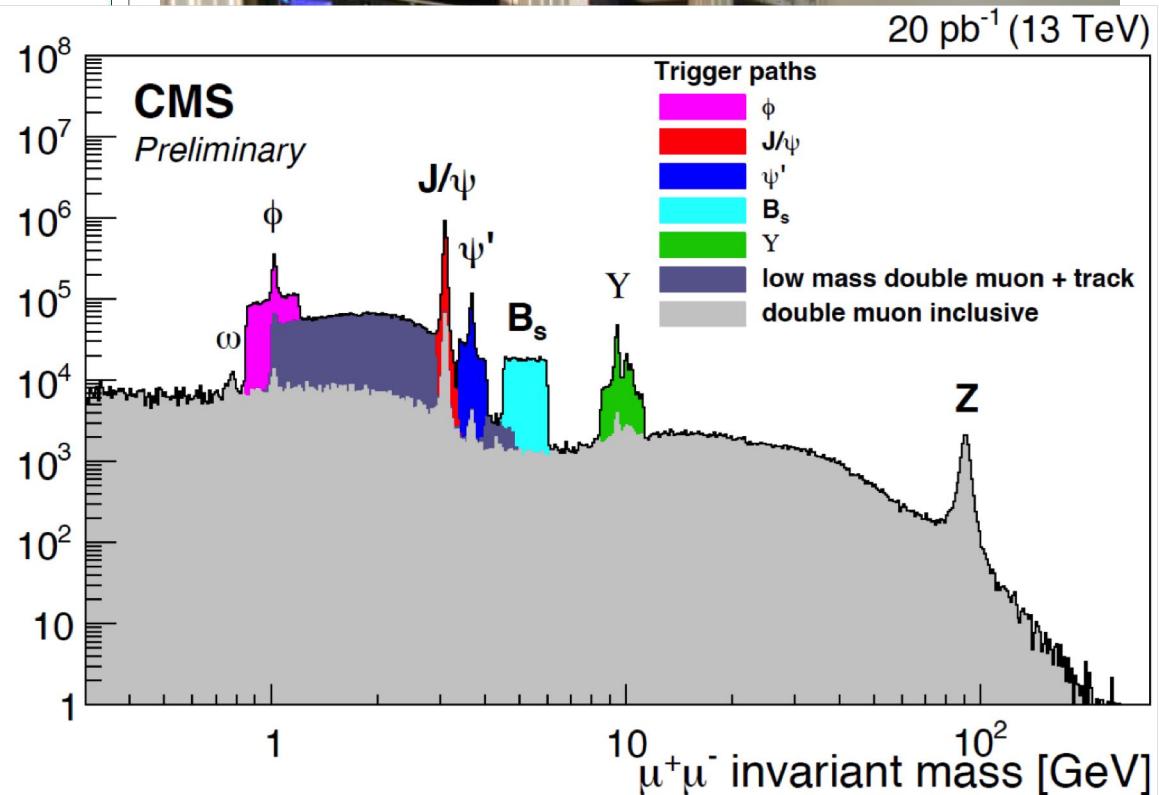
Rossi “approximation B” (1952), simplification by Heitler

# Was passiert wenn Teilchen kollidieren?

...ein “Ereignis”:

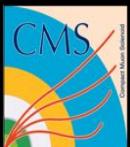
1. Aufnahme
2. Datenreduktion
3. Verteilung
4. Analyse-Software
5. Auswertung
6. Ergebnis

```
std::vector<Sample*> samples;
std::vector<std::vector<float>> countABCD;
samples.clear();
cout<<prefix<<"creating samples and fwlite::ChainEvents:"<<endl;
std::vector<float> zerovec;
```



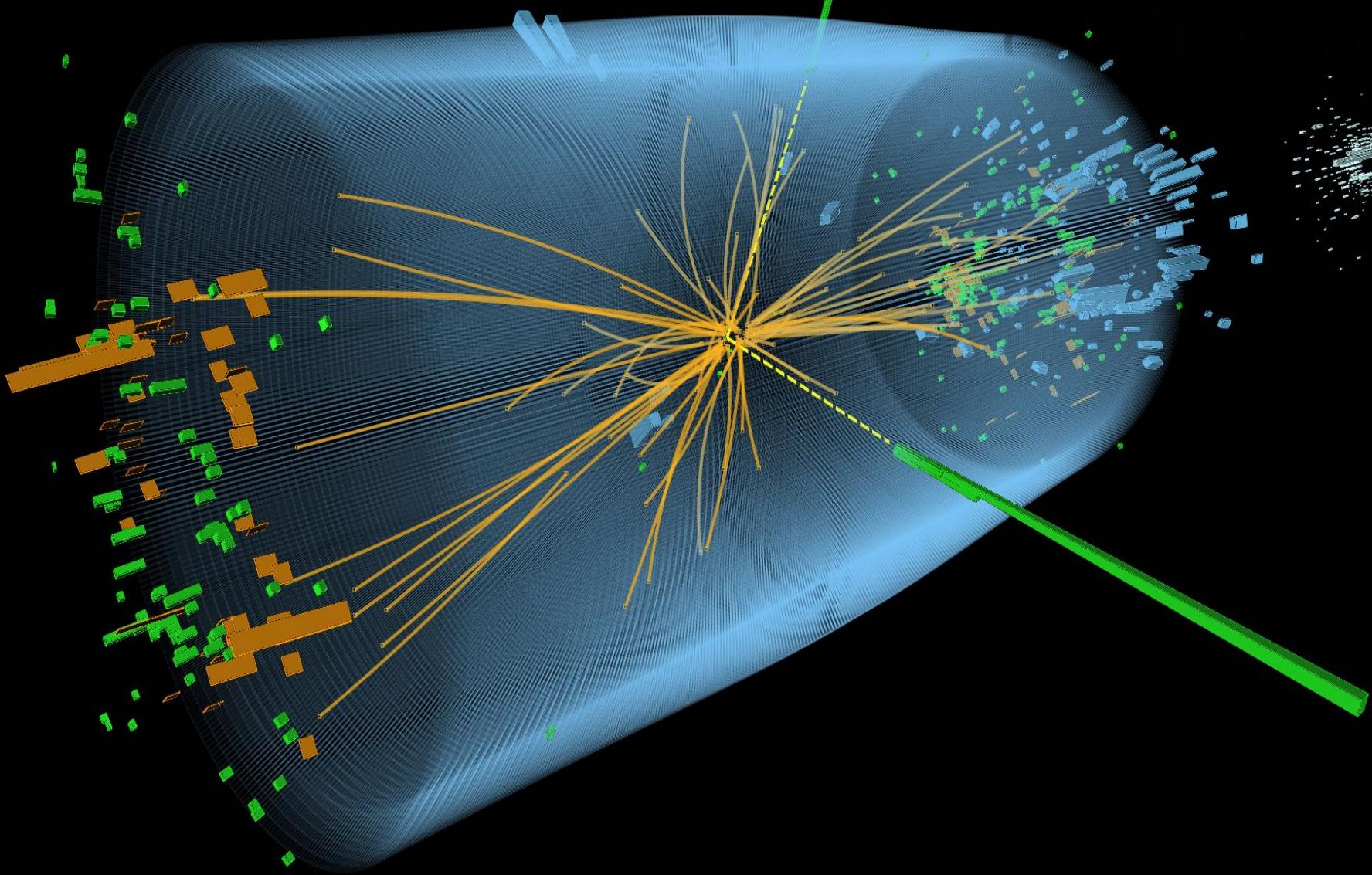
Ein “realistisches” Bild von 100 Milliarden pp Kollisionen

```
if (!hasNoElectron) continue;
cout<<prefix<<"Electron passed: "<<elec->id()<<endl;
```

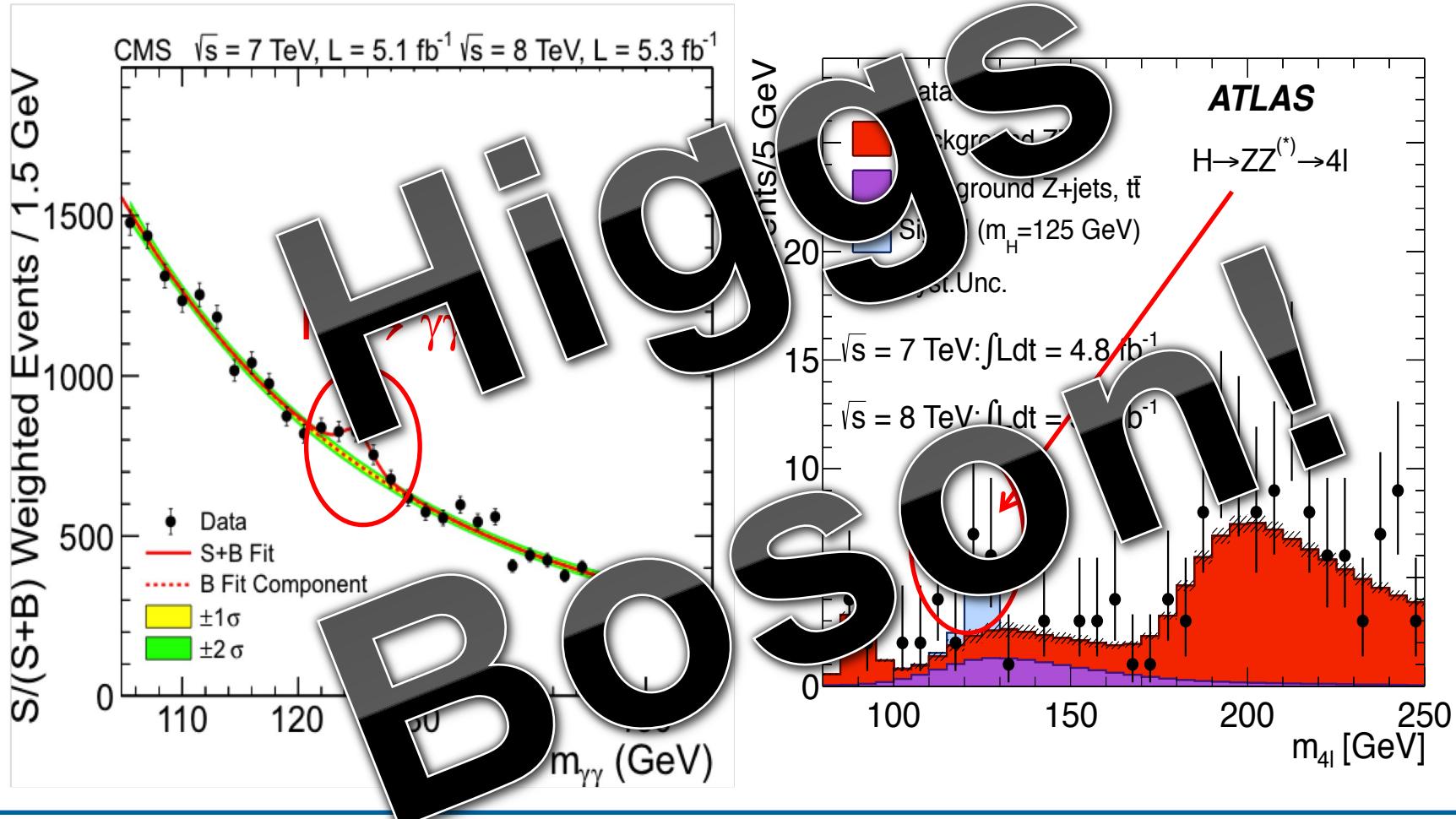


CMS Experiment at the LHC, CERN  
Data recorded: 2012-May-13 20:08:14.621490 GMT  
Run/Event: 194108 / 564224000

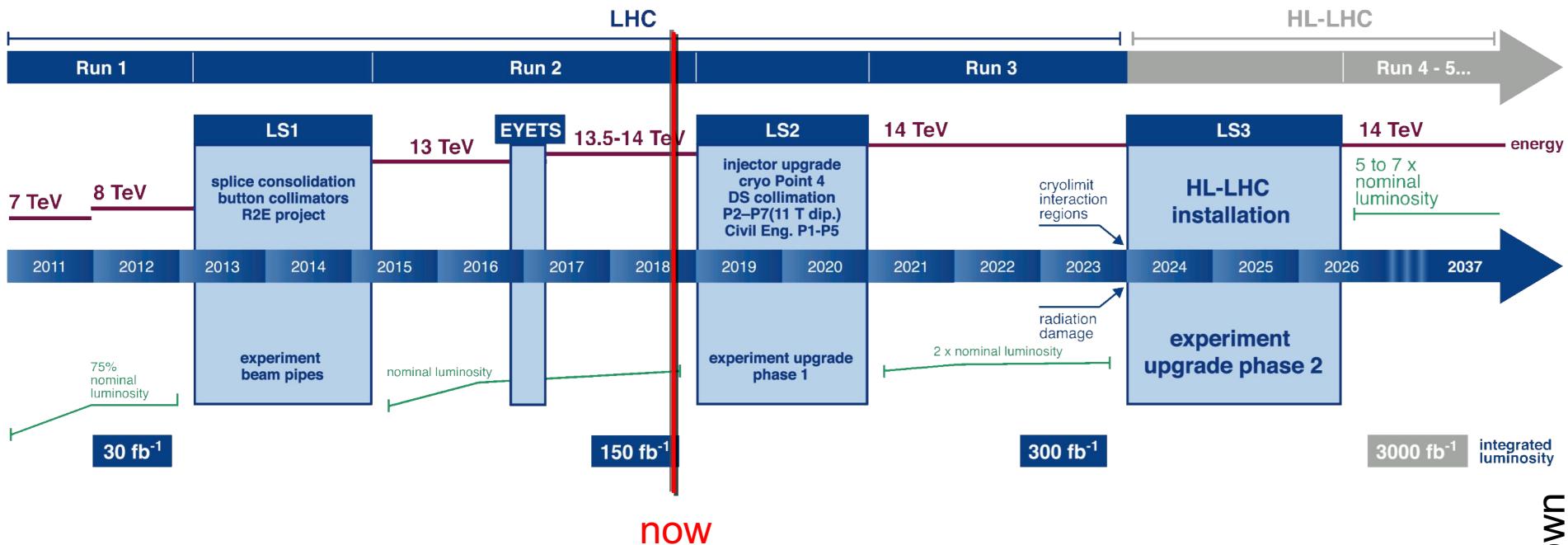
H →  $\gamma\gamma$



# Bekanntgabe der Entdeckung eines neuen Teilchens (4. Juli 2012)



# Weiterer Betrieb des LHC

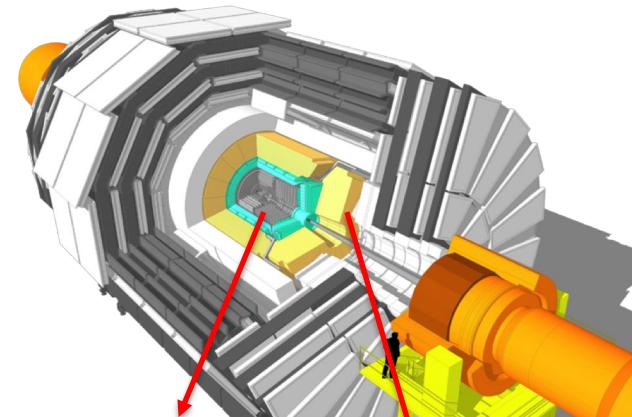


- Wiederinbetriebnahme Anfang 2015 mit (fast) voller Kollisionsenergie (13 TeV)
- Planungen gehen bis 2037
- 3-4 Jahre Betrieb, danach Wartungs- und Erweiterungsarbeiten

LS ... long shutdown

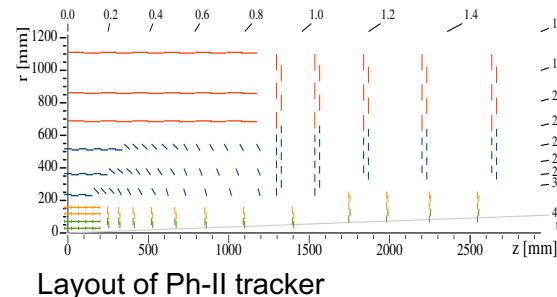
## Long Shutdown 3 (LS3) scheduled for 2024-2025

- LHC accelerator upgrade to High-Luminosity (HL)-LHC
- Upgrade of experiments necessary
  - Existing systems reach end of life (radiation damage)
  - Increase in luminosity at HL-LHC:  $300 \rightarrow 3000 \text{ fb}^{-1}$



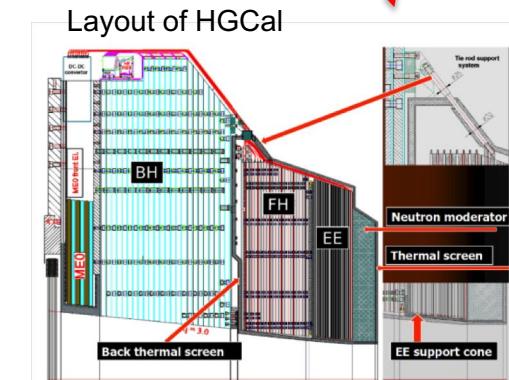
## Phase-II Upgrade of CMS:

- Complete exchange of Outer Tracker  
 $\rightarrow 200 \text{ m}^2$  Si Sensors needed
- New Highly Granularity Calorimeter (HGCal)  
 $\rightarrow 600 \text{ m}^2$  Si Sensors (8 inch)



## With our expertise we play a key role in both projects

- Sensor Design, Simulation
- Electrical Characterization for both, R&D and series
- Quality Assurance during mass production
- Co-Convenors of sensor development working groups



## Why do we need an upgrade?

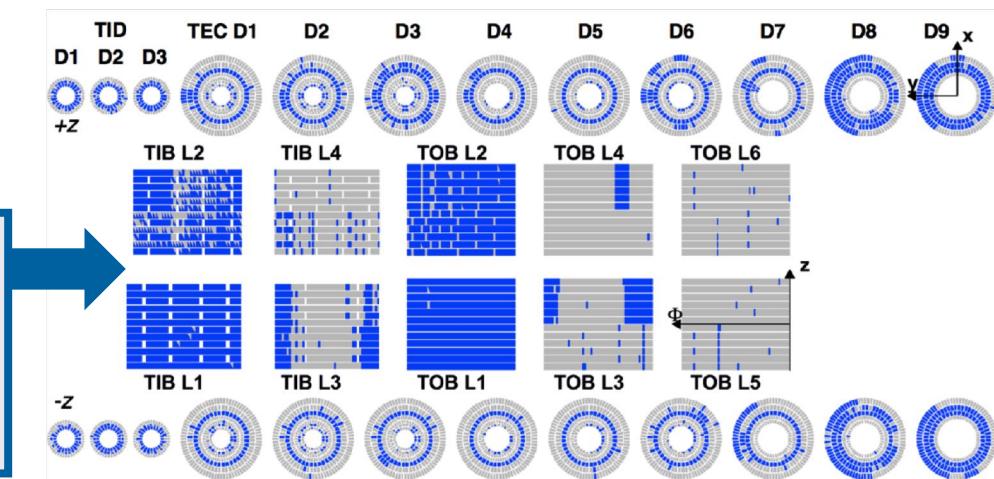
1. To fully exploit the high luminosity conditions
2. Design limitations of current tracker will be exceeded by far

	Design limitations of current Tracker	HL-LHC conditions
Pileup	20-30	140-200
int. lumi.	< 1000 fb <sup>-1</sup>	3000-4000 fb <sup>-1</sup>

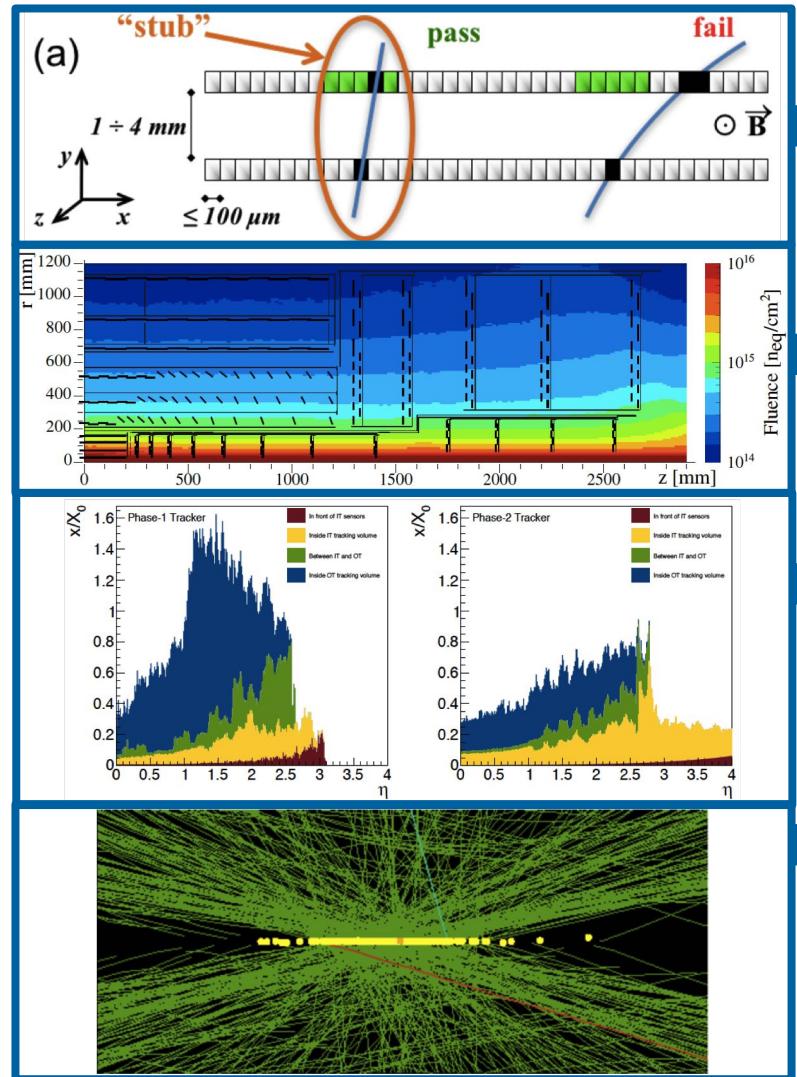
3. Radiation damage will lead to many non-functional modules

→ Increased leakage current  
cannot be compensated  
by cooling anymore

Simulation of non-functional  
modules in the current tracker  
(blue) after 1000 fb<sup>-1</sup> integrated  
luminosity.



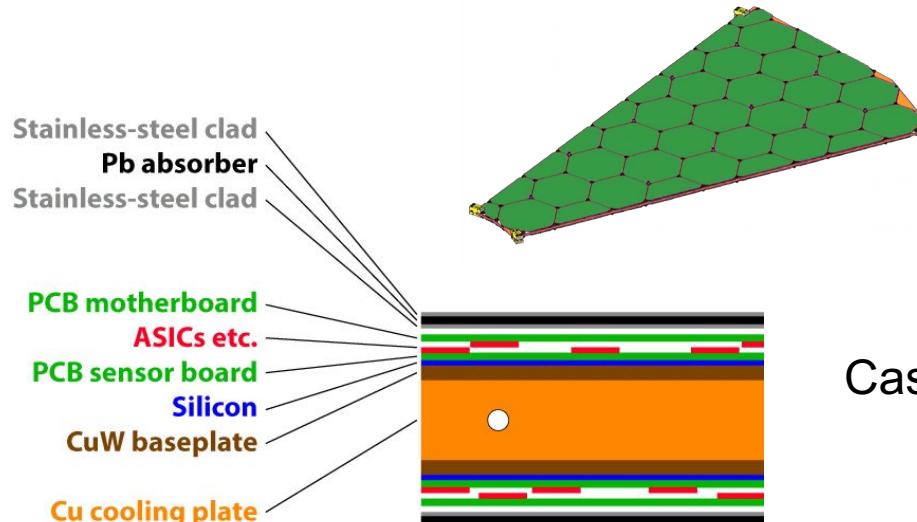
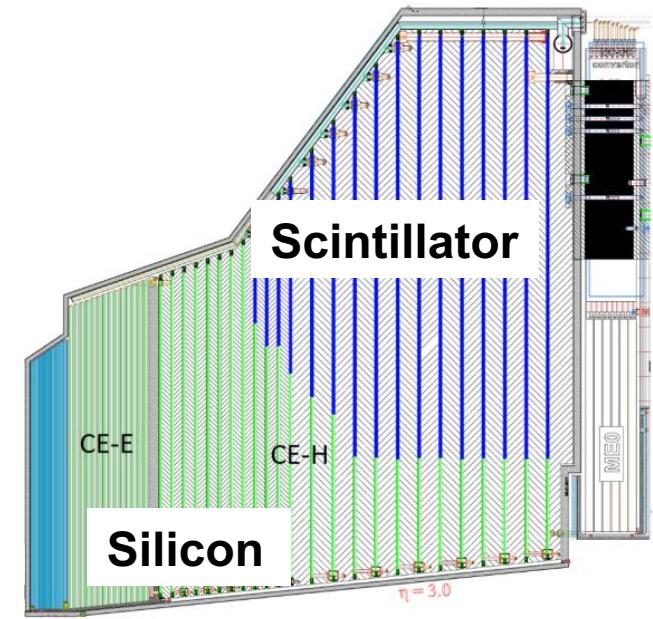
## Requirements for the upgrade



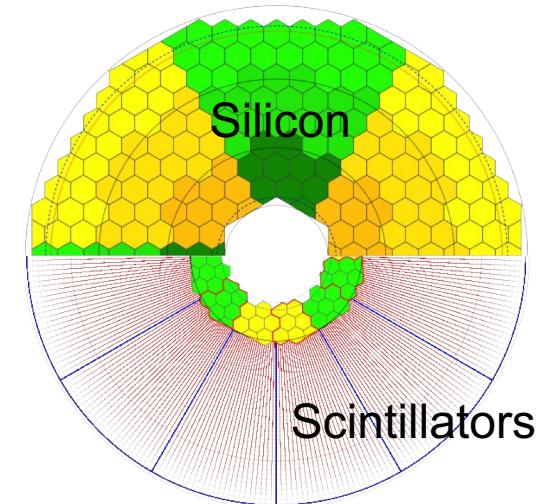
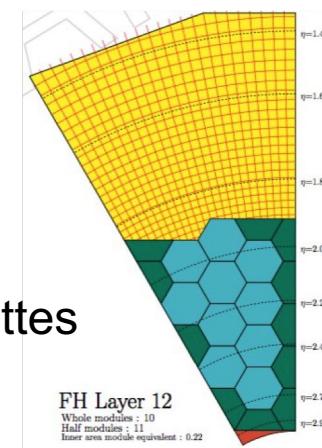
- Maintain physics performance
  - Track trigger concept
- Increase radiation hardness
  - $2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2 \rightarrow \text{Pixel}$
  - $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \rightarrow \text{Strips}$
- Reduce material budget
- Extend tracking acceptance
  - $|\eta| = 2.4 \rightarrow |\eta| = 4$
- Increase granularity
  - Keep channel occupancy below 1 %

## CMS is planning to build a High Granularity Calorimeter for Phase-II at HL-LHC

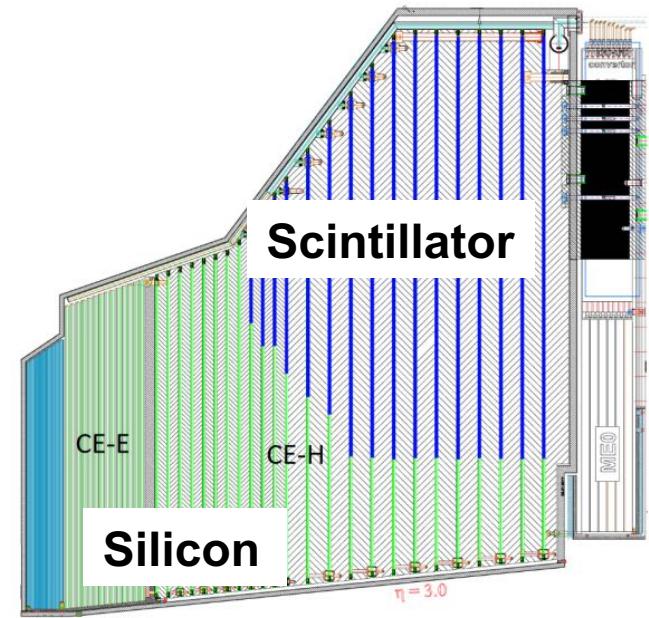
- Covering  $1.5 < \eta < 3.0$
- Features unprecedented transverse and longitudinal segmentation
  - Silicon in high radiation areas
  - Scintillating tiles in the low-radiation region of CE-H (Mixed Silicon-Scintillator cassettes)



Cassettes



	CE-E	CE-H (Si)	CE-H (Si + Scint)
<b>Active</b>	Silicon sensors	Scintillators	
<b>Absorber</b>	Lead	Stainless steel	
<b>Depth</b>	$26X_0 / 1.7\lambda$	$9\lambda$	
<b>Layers</b>	28	8	16
<b>Weight</b>	23t	205t	



	Silicon sensors	Scintillators
Area	<b>600 m<sup>2</sup></b>	500 m <sup>2</sup>
# Modules	25,000	2500
Channels Size	0.5-1 cm <sup>2</sup>	4-30 cm <sup>2</sup>
# Channels	6 Mio	400k
Op. temperature	-30° C	-30° C



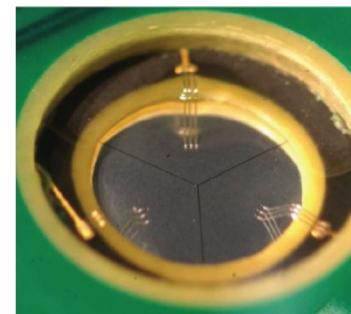
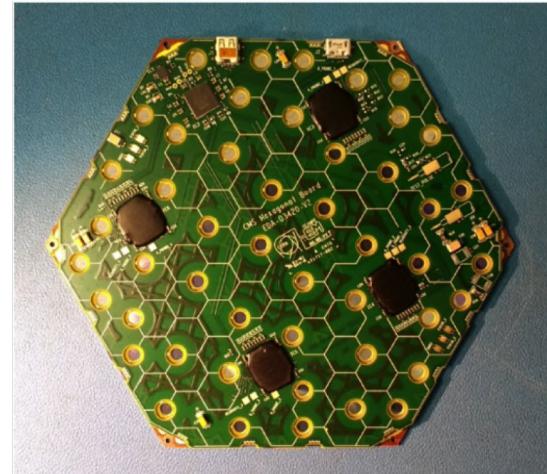
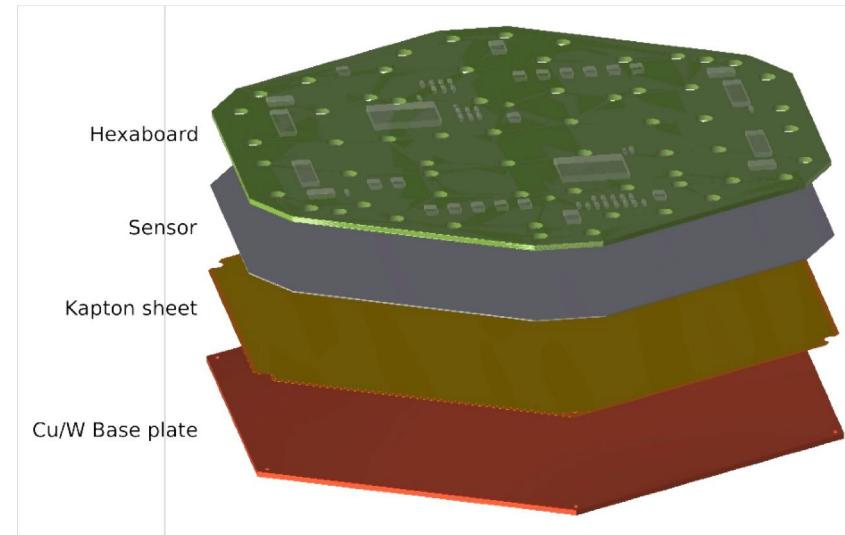
Silicon detector module is of hexagonal shape and is a stack of:

- PCB: “hexaboard”: contains FE ASICs and connects to Si sensor via wire-bonds through holes
- Hexagonal Si-Sensor
- Kapton sheet for HV isolation
- Copper/Tungsten Base plate

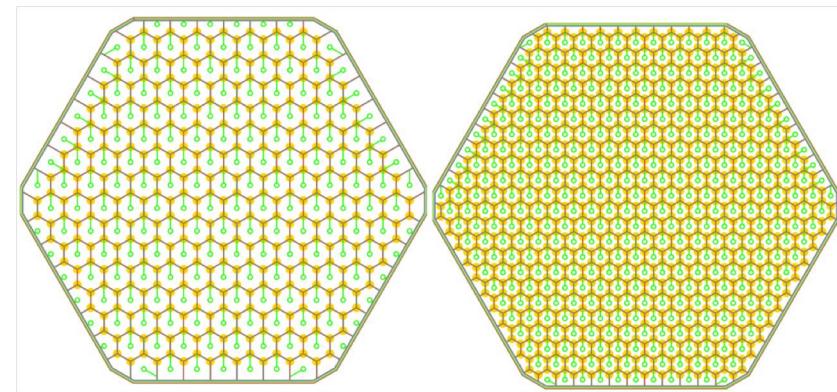
The whole module sits on a copper cooling plate with CO<sub>2</sub> cooling channels

Additional components:

- 2<sup>nd</sup> PCB (not shown): Motherboard for powering, data concentration, trigger generation and bi-directional communication
- Trigger/data transfer: low-power GBT links (IpGBT)

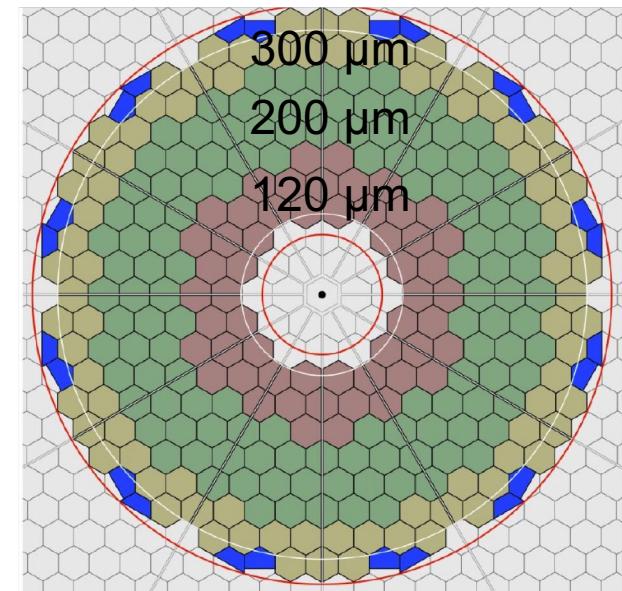
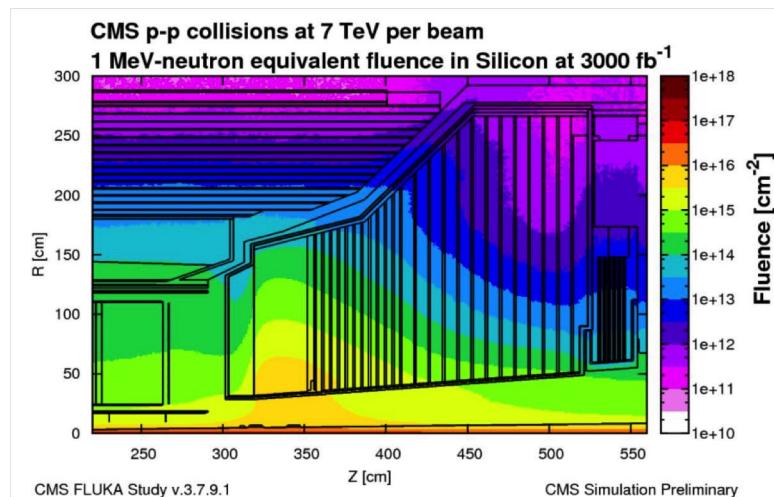


- Hexagonal sensor geometry as largest tileable polygon
  - maximize use of circular wafer
  - Minimize ratio of periphery to surface area
  - Truncated tips (“mouse-bites”) used for module mounting → Further increase use of wafer surface
- Each sensor consists of individual pads (cells)
- Three thicknesses based on radiation and occupancy considerations



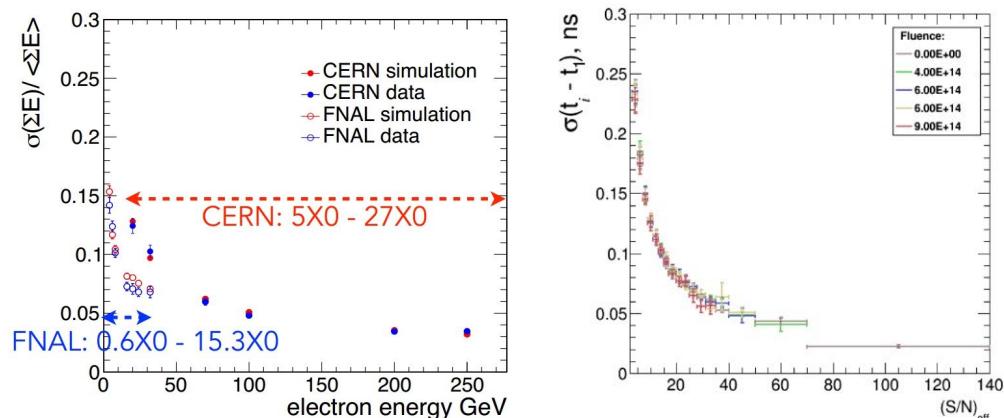
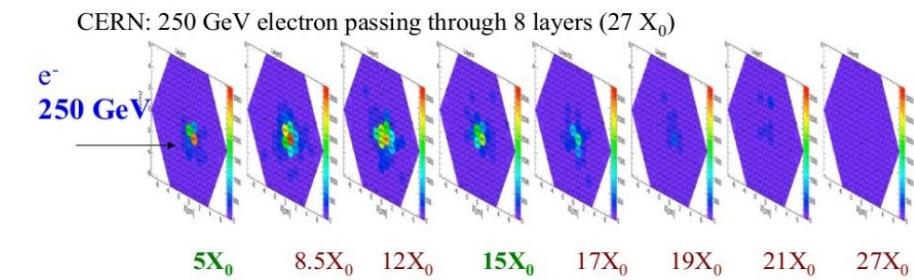
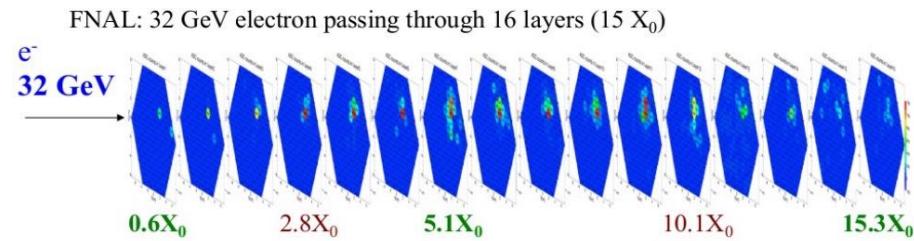
Thickness [µm]	# cells	Cell size [cm <sup>2</sup> ]	Cell C [pF]	Bulk polarity	Expected Fluence [E15 n cm <sup>-2</sup> ]	# wafers (8 inch)	# partial 8 inch wafers
300	192	1.18	45	p (n)	0.1-0.5	13164	1284
200	192	1.18	65	p	0.5-2.5	8712	144
120	432	0.52	50	p	2-7	3000	324
						<b>Total:</b>	<b>24876</b>
							<b>1752</b>

- Fluence is n-dominated w.r.t. charged hadrons (90%/10%)
- Deployment of thinner sensors in the higher fluence regions of the calorimeter
  - improved charge collection
  - reduced leakage current
- Typical signals in calorimeter much higher than MIPs
  - MIP sensitivity needed for energy calibration (e.g. isolated muons)



Beam tests at FNAL and CERN performed with modules built on TP geometry (6" sensors) to study

- Longitudinal and transverse shower shapes
- Energy, position, time resolution
- Achieved resolution for:
  - Energy: below  $\sim 7\%$ , for e energy  $> 50$  GeV
  - Position: below  $\sim 2$ mm, for e energy  $> 50$  GeV
  - Time:  $\sim 20$  ps



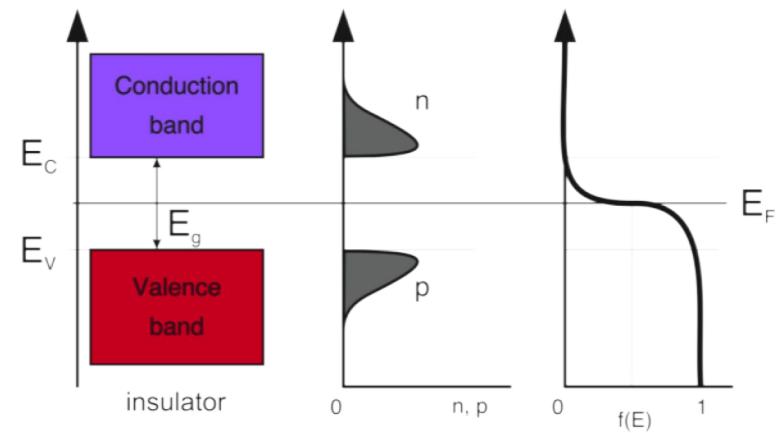
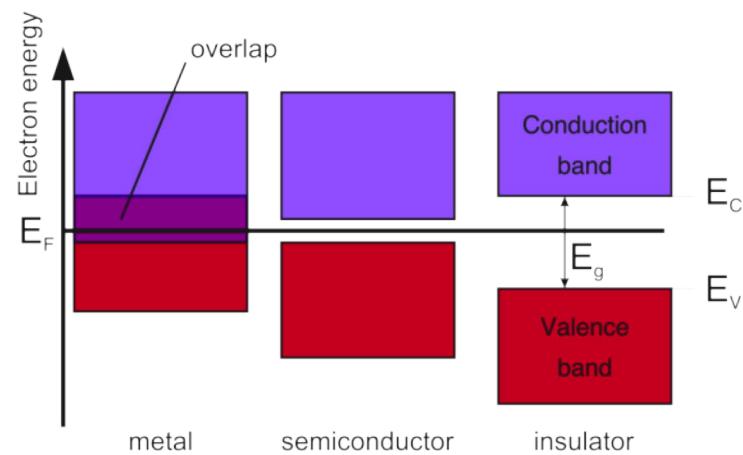
# SILIZIUMDETEKTOREN

- **Germanium:**
  - Used in nuclear physics
  - Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)
- **Silicon:**
  - Can be operated at room temperature
  - Synergies with micro electronics industry
  - Standard material for vertex and tracking detectors in high energy physics
- **Diamond (CVD or single crystal):**
  - Allotrope of carbon
  - Large band gap (requires no depletion zone)
  - very radiation hard
  - Disadvantages: low signal and high cost

- Compound semiconductors consist of
  - two (binary semiconductors) or
  - more than two atomic elements of the periodic table.
- Depending on the column in the periodic system of elements one differentiates between
  - IV-IV- (e.g.  $SiGe$ ,  $SiC$ ),
  - III-V- (e.g.  $GaAs$ )
  - II-VI compounds ( $CdTe$ ,  $ZnSe$ )

	I	II	III	IV	V	VI	VII	VIII
1	1 H							2 He
2	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	113 Uut	114 Uuq	114 Uup	115 Uuh	117 Uus	118 Uuo

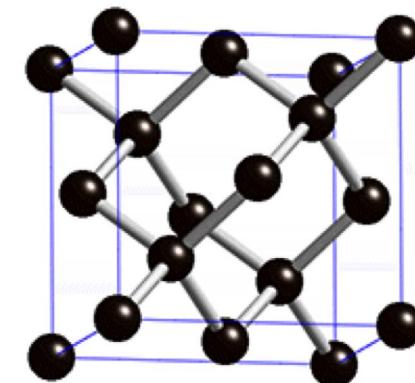
- Semiconductor
- Moderate bandgap  $E_g = 1.12\text{eV}$
- Energy to create e/h pair =  $3.6\text{eV}$ 
  - Low compared to gases used for ionization chambers or proportional counters  
(e.g. Argon gas =  $15\text{eV}$ )
- High density and atomic number
  - Higher specific energy loss → Thinner detectors
- High carrier mobility → Fast!
  - Less than  $30\text{ns}$  to collect entire signal
- Industrial fabrication techniques



## Si, Ge and diamond

- Group IV elements
- Crystal structure: *diamond lattice*
  - 2 nested sub-lattices
  - shifted by one quarter along the diagonal of the cube.
  - Each atom is surrounded by **four equidistant neighbors**.
  - Lattice parameter  $a=0.54\text{nm}$

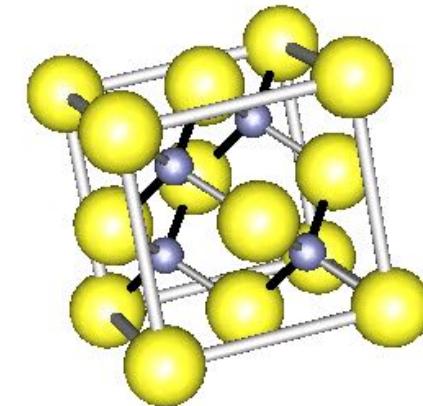
Diamond lattice



## Most III-V semiconductors (e.g. GaAs)

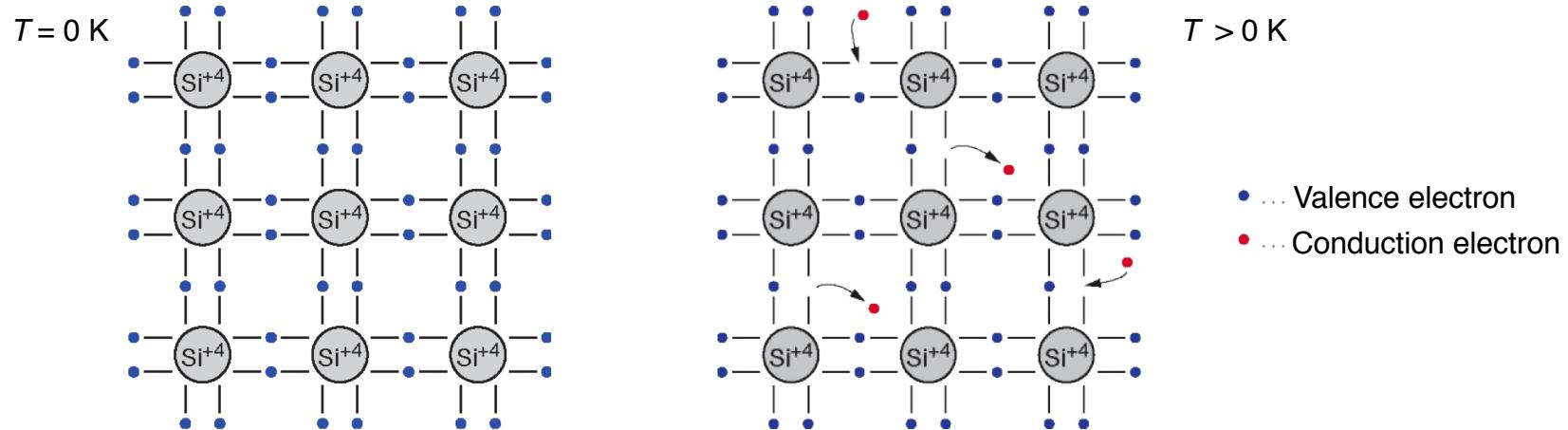
- *zincblende lattice*
  - similar to the diamond lattice
  - except that each sub-lattice consists of one element.

Zincblende lattice



# Bond model of semiconductors

Example of column IV elemental semiconductor (2-dimensional projection) :



Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form **covalent bonds**.

- At low temperature all electrons are bound
- At higher temperature thermal vibrations break some of the bonds → free e<sup>-</sup> cause conductivity (electron conduction)
- The remaining open bonds attract other e<sup>-</sup> → The “holes” change position (hole conduction)

## Intrinsic carrier concentration

- Due to the small band gap in semiconductors electrons already occupy the conduction band at room temperature.
- Electrons from the conduction band may recombine with holes.
- A **thermal equilibrium** is reached between **excitation** and **recombination**: Charged carrier concentration  $n_e = n_h = n_i$   
This is called intrinsic carrier concentration:

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

$N_C, N_V$  ... effective density of states at the conduction, valence band edge

In ultrapure silicon the intrinsic carrier concentration is  $1.45 \cdot 10^{10} \text{ cm}^{-3}$ .  
With approximately  $10^{22} \text{ Atoms/cm}^3$  about 1 in  $10^{12}$  silicon atoms is ionized.

# Drift velocity and mobility

## Drift velocity

For electrons:

$$\vec{v}_n = -\mu_n \cdot \vec{E}$$

and for holes:

$$\vec{v}_p = \mu_p \cdot \vec{E}$$

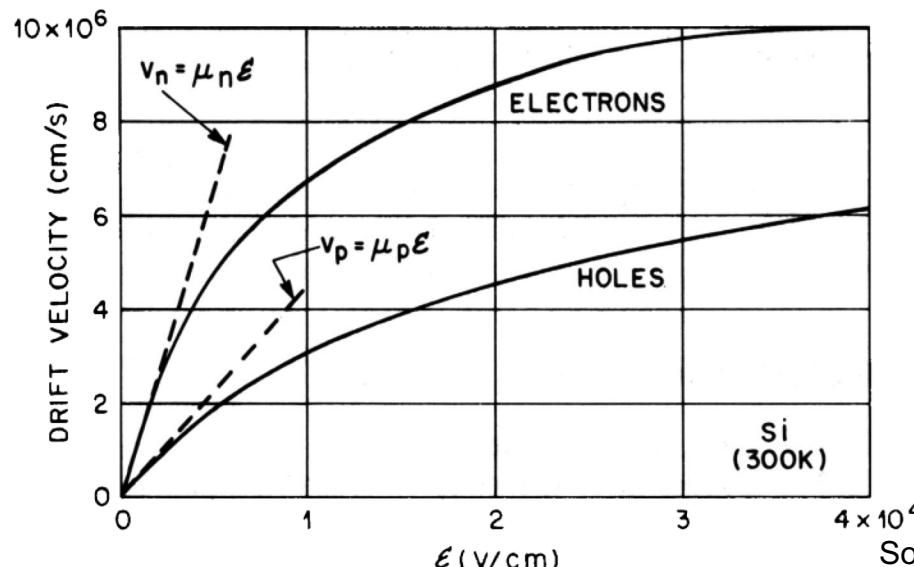
## Mobility

For electrons:

$$\mu_n = \frac{e \tau_n}{m_n}$$

and for holes:

$$\mu_p = \frac{e \tau_p}{m_p}$$



- e ... electron charge
- E ... external electric field
- $m_n, m_p$  ... effective mass of  $e^-$  and holes
- $\tau_n, \tau_p$  ... mean free time between collisions  
for  $e^-$  and holes (carrier lifetime)

Source: S.M. Sze, *Semiconductor Devices*, J. Wiley & Sons, 1985

# Resistivity

Specific resistivity is a measure of silicon purity:

$$\rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)}$$

$n_e, n_h$  ... Charge carrier density for electrons and holes  
 $\mu_n, \mu_p$  ... Mobility for electrons and holes  
 $e$  ... elementary charge

Carrier mobilities:  $\mu_p(\text{Si, 300 K}) \approx 450 \text{ cm}^2/\text{Vs}$   
 $\mu_n(\text{Si, 300 K}) \approx 1450 \text{ cm}^2/\text{Vs}$

The charge carrier concentration in pure silicon (i.e. intrinsic Si) for  $T = 300 \text{ K}$  is:  $n_e = n_h \approx 1.45 \cdot 10^{10} \text{ cm}^{-3}$

This yields an intrinsic resistivity of:

$$\rho \approx 230 \text{ k}\Omega\text{cm}$$

# Constructing a Detector

One of the most important parameter of a detector is the **signal-to-noise-ratio** (SNR). A good detector should have a large SNR.

However this leads to **two contradictory requirements**:

- **Large signal**
  - low ionization energy -> small band gap
- **Low noise**
  - very few intrinsic charge carriers -> large band gap

An optimal material should have  $E_g \approx 6 \text{ eV}$ .

In this case the conduction band is almost empty at room temperature and the band gap is small enough to create a large number of  $e^-h^+$  pairs through ionization.

Such a material exist, it is **Diamond**. However even artificial diamonds (e.g. CVD diamonds) are too expensive for large area detectors.

# Constructing a Detector (cont.)

Let's make a simple calculation for silicon:

- Mean ionization energy  $I_0 = 3.62 \text{ eV}$ ,
- mean energy loss per flight path of a mip  $dE/dx = 3.87 \text{ MeV/cm}$

Assuming a detector with a thickness of  $d = 300 \mu\text{m}$  and an area of  $A = 1 \text{ cm}^2$ .

- **Signal of a mip in such a detector:**

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6 \text{ eV/cm} \cdot 0.03 \text{ cm}}{3.62 \text{ eV}} \approx 3.2 \cdot 10^4 \text{ e}^- \text{h}^+ - \text{pairs}$$

- **Intrinsic charge carrier in the same volume ( $T = 300 \text{ K}$ ):**

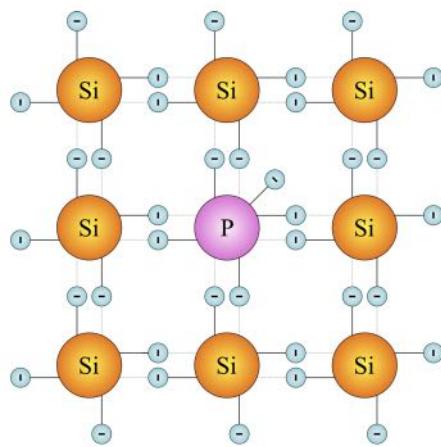
$$n_i d A = 1.45 \cdot 10^{10} \text{ cm}^{-3} \cdot 0.03 \text{ cm} \cdot 1 \text{ cm}^2 \approx 4.35 \cdot 10^8 \text{ e}^- \text{h}^+ - \text{pairs}$$

**Result:** The number of thermal created  $\text{e}^- \text{h}^+$ -pairs (noise) is four orders of magnitude larger than the signal.

We have to remove the charge carriers

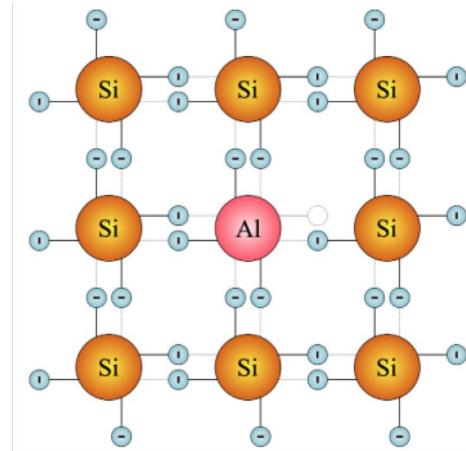
-> Depletion zone in reverse biased **pn junctions**

# Doping: n- and p-type Silicon



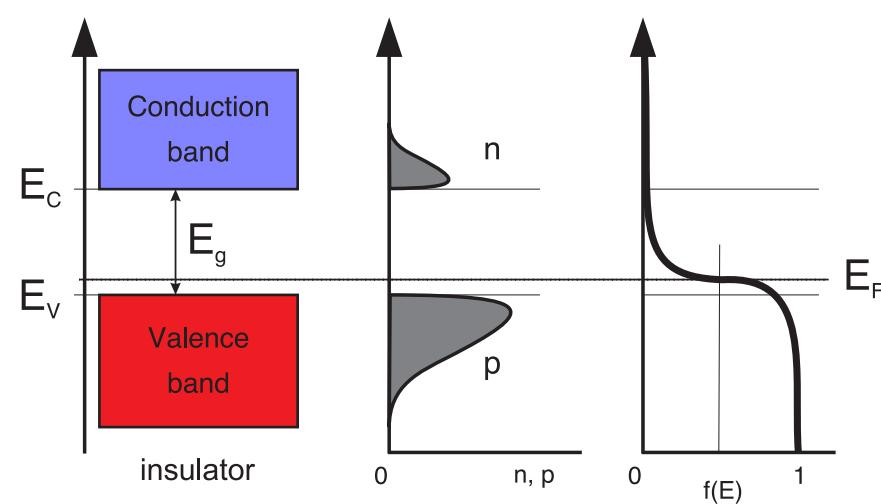
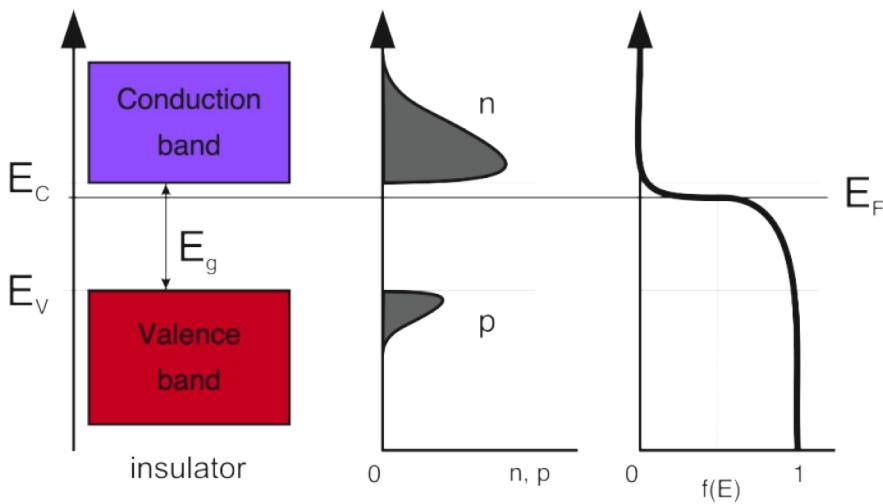
## n-type:

- Dopants: Elements with 5 valence electrons, e.g. Phosphorus
- Donators
- Electron abundance



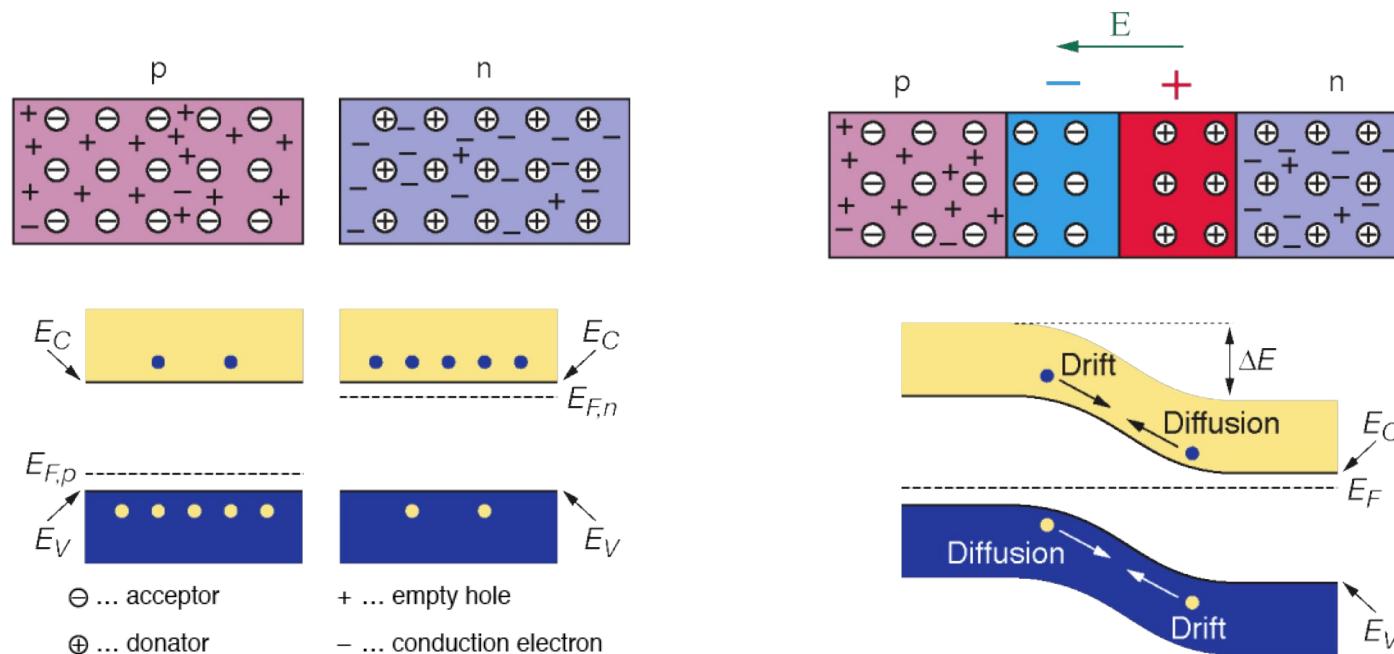
## p-type:

- Dopants: Elements with 3 valence electrons, e.g. Aluminum
- Acceptors
- Electron shortage



# Creating a p-n junction

At the interface of an n-type and p-type semiconductor the difference in the Fermi levels cause diffusion of excessive carries to the other material until thermal equilibrium is reached. At this point the Fermi level is equal. The remaining ions create a **space charge region** and an electric field stopping further diffusion. The stable space charge region is free of charge carries and is called the **depletion zone**.



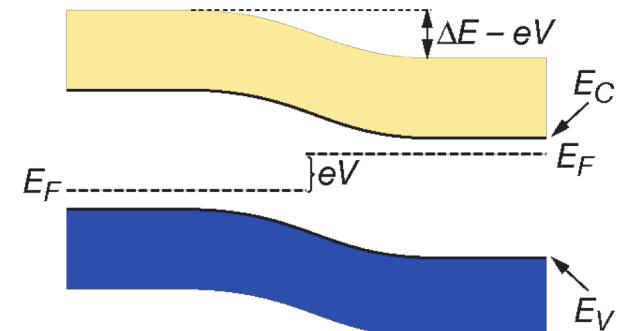
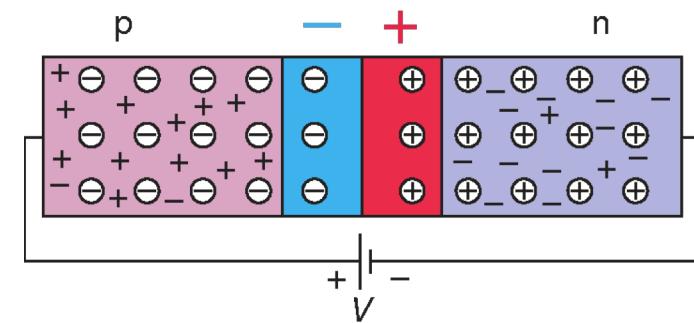
# Operation of a pn-junction with forward bias

Applying an external voltage  $V$  with the anode to p and the cathode to n e- and holes are refilled to the depletion zone. The **depletion zone becomes narrower** (forward biasing)

## Consequences:

- The potential barrier becomes smaller by  $eV$
- Diffusion across the junction becomes easier
- The current across the junction increases significantly.

p-n junction with forward bias

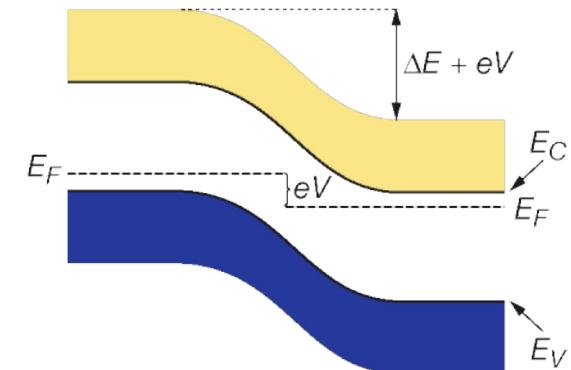
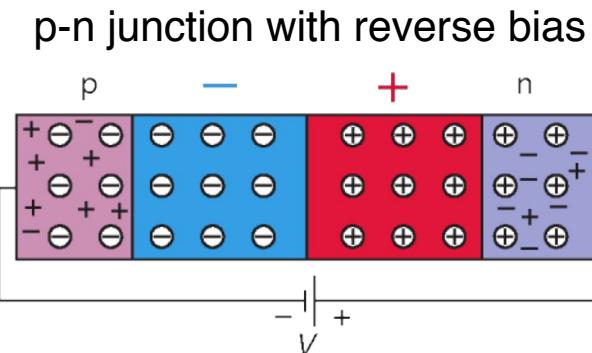


# Operation a pn-junction with reverse bias

Applying an external voltage  $V$  with the cathode to p and the anode to n e- and holes are pulled out of the depletion zone. The **depletion zone becomes larger** (reverse biasing).

## Consequences:

- The potential barrier becomes higher by  $eV$
- Diffusion across the junction is suppressed.
- The current across the junction is very small (“leakage current”)



➤ This is the way we operate our semiconductor detector!

# Width of the depletion zone

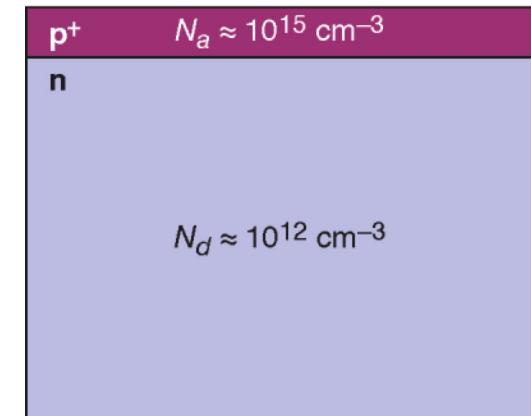
Effective doping concentration in typical silicon detector with p<sup>+</sup>-n junction

- $N_a = 10^{15} \text{ cm}^{-3}$  in p+ region
- $N_d = 10^{12} \text{ cm}^{-3}$  in n bulk.

**Without external voltage:**

$$W_p = 0.02 \mu\text{m}$$

$$W_n = 23 \mu\text{m}$$



**Applying a reverse bias voltage of 100 V:**

$$W_p = 0.4 \mu\text{m}$$

$$W_n = 363 \mu\text{m}$$

Width of depletion zone in n bulk:

$$W \approx \sqrt{2\varepsilon_0 \varepsilon_r \mu \rho |V|}$$

with  $\rho = \frac{1}{e \mu N_{eff}}$

$V$  ... External voltage  
 $\rho$  ... specific resistivity  
 $\mu$  ... mobility of majority charge carriers  
 $N_{eff}$  ... effective doping concentration

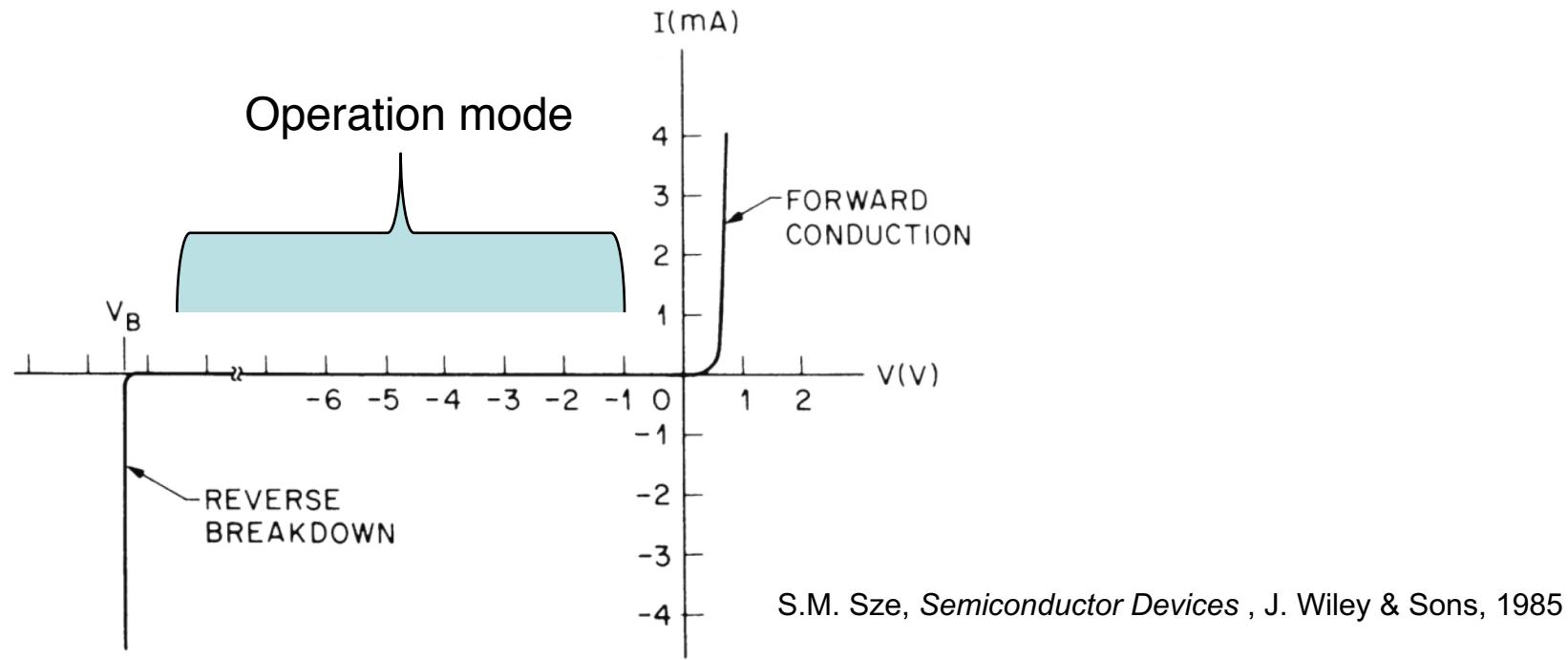
# Current-voltage characteristics

Typical current-voltage of a p-n junction (diode): exponential current increase in forward bias, small saturation in reverse bias.

Ideal diode equation:  
(Shockley-equation)

$$I = I_0 \cdot \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right]$$

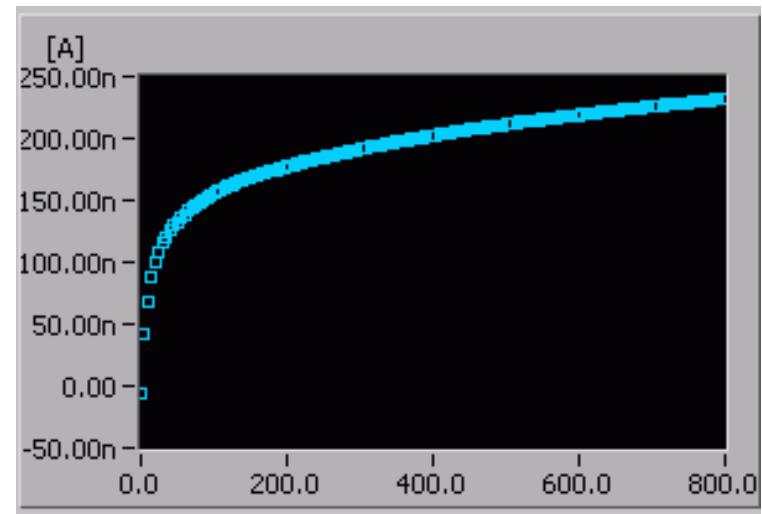
$I_0$  ... reverse saturation current



# Reverse current

- **Diffusion current**
  - From generation at edge of depletion region
  - Negligible for a fully depleted detector
- **Generation current**
  - From thermal generation in the depletion region
  - Reduced by using pure and defect free material
    - high carrier lifetime
  - Must keep temperature low & controlled

IV curve of diode in reverse mode:



$$j_{gen} = \frac{1}{2} q \frac{n_i}{\tau_0} W \quad j_{gen} \propto T^{3/2} \exp\left(-\frac{1}{2kT}\right)$$

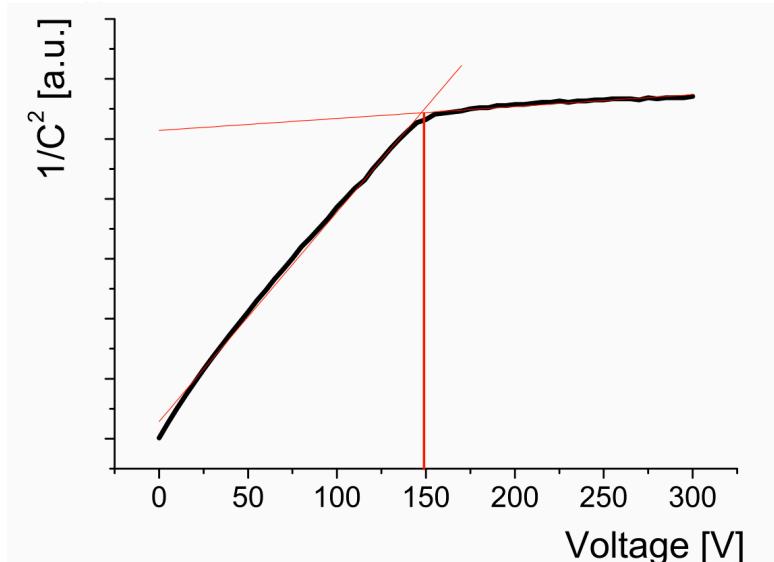
$j_{gen} \times 2 \text{ for } \Delta T = 7K$

# Detector Capacitance and Full Depletion

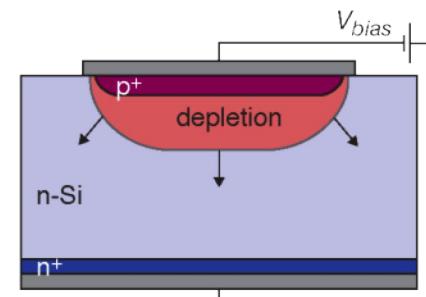
- Capacitance is similar to parallel-plate capacitor
- Fully depleted detector capacitance defined by geometric capacitance

$$C = \frac{\epsilon_0 \epsilon_r \cdot A}{W} = \sqrt{\frac{e \epsilon_0 \epsilon_r N_a N_d}{2(N_a + N_d) \cdot |V|}} \cdot A$$

$$C = \sqrt{\frac{\epsilon_0 \epsilon_r}{2\mu\rho|V|}} \cdot A$$



$\rho$  ... bulk resistivity  
 $\mu$  ... charge mobility  
 $V$  ... voltage  
 $A$  ... junction area

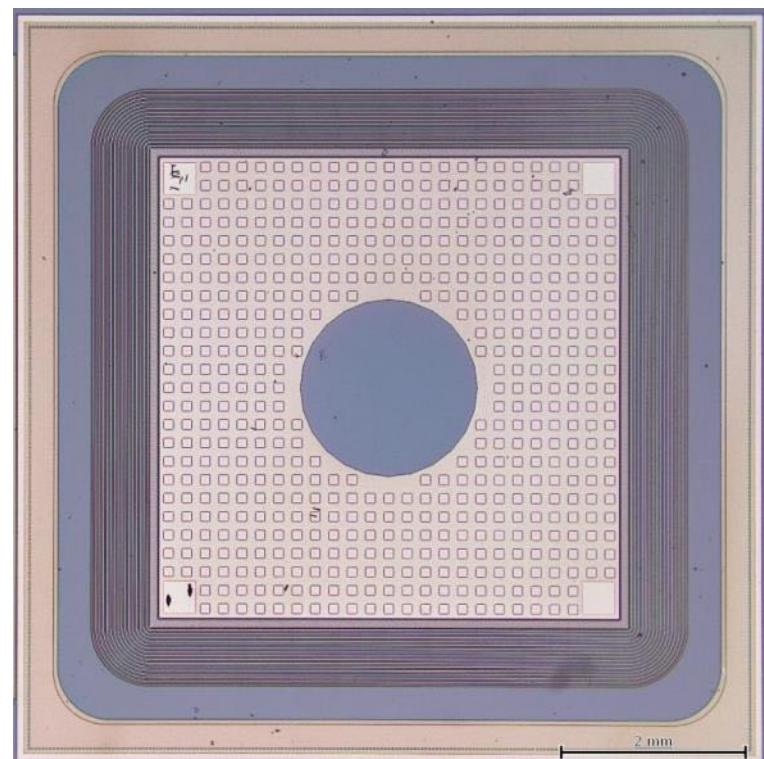
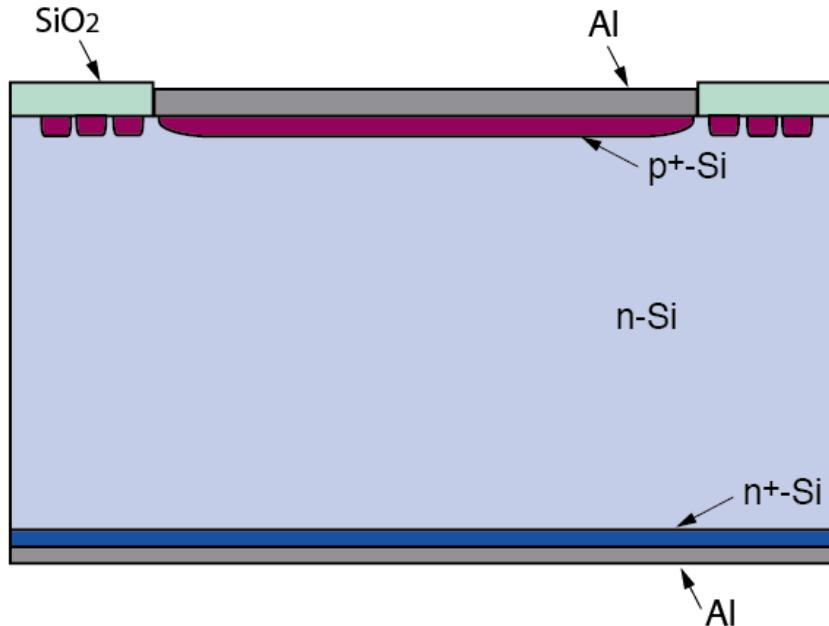


# SINGLE SIDED STRIP DETECTORS

# Pad Detector

The most simple detector is a large surface diode with guard ring(s).

- no position resolution
- Good for basic tests (IV, CV)

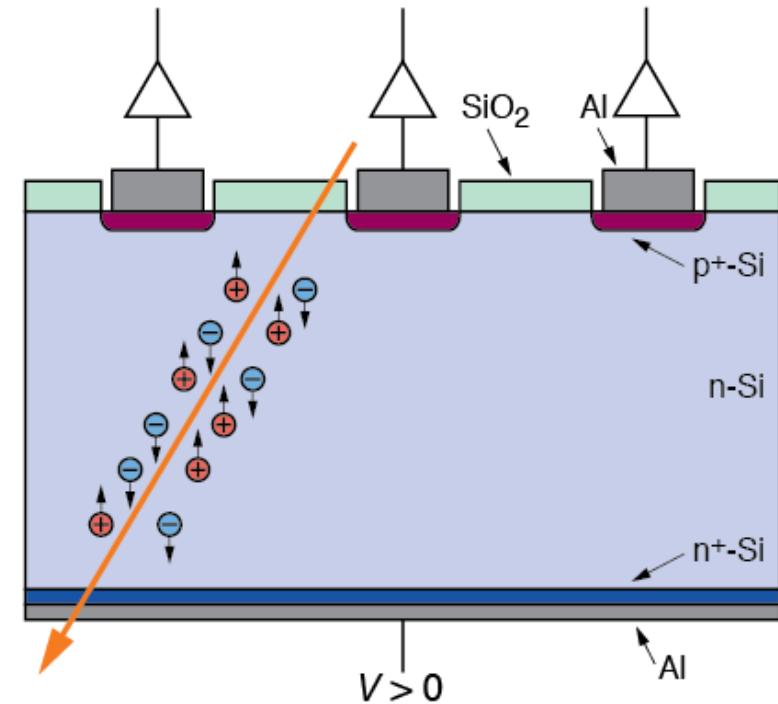


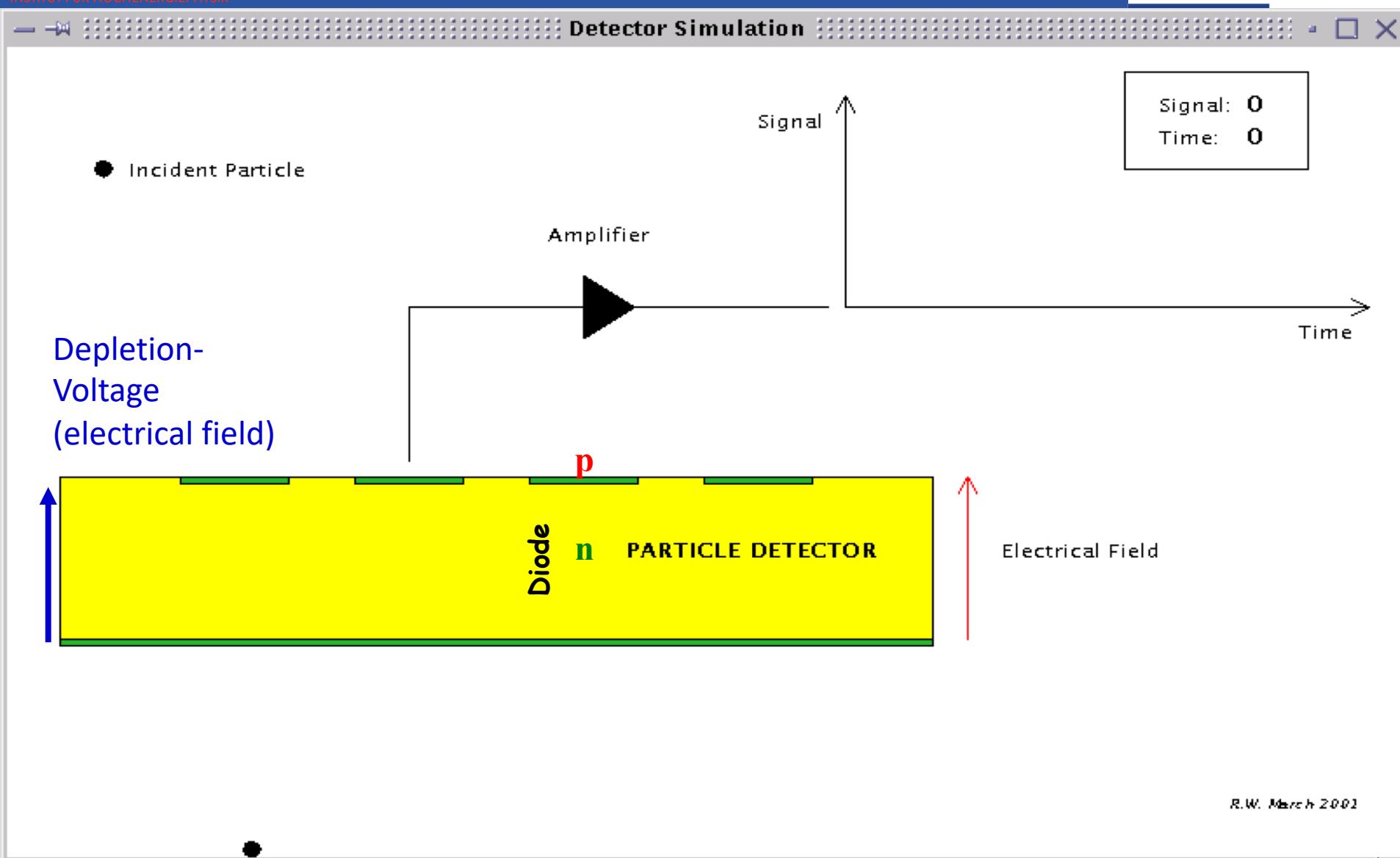
# DC coupled strip detector

- Charged particles traversing sensor create  $e^-/h^+$  pairs in the depletion region
- These charges drift to the electrodes.
- The drift (current) creates the signal which is amplified by an amplifier connected to each strip.
- From the signals on the individual strips the position of the through going particle is deduced.

Typical n-type Si strip detector:

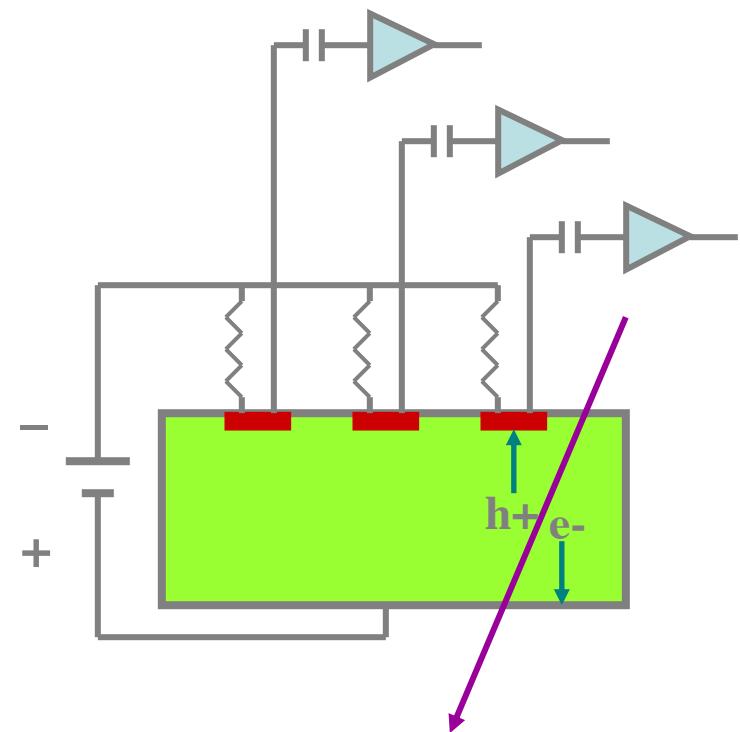
- n-type bulk:  $\rho > 2 \text{ k}\Omega\text{cm}$
- thickness  $300 \mu\text{m}$
- Operating voltage  $< 200 \text{ V}$ .
- $n^+$  layer on backplane to avoid Schottky contact and improve ohmic contact
- Aluminum metallization





R.W. March 2001

- AC-coupled sensors create two electrical circuits on the sensor:
  - Readout circuit into amplifier (AC current)
  - Biassing circuit (DC current)
- Method to connect readout strips to bias voltage source:
  - Poly-silicon resistor
  - Punch-through
  - FOXFET

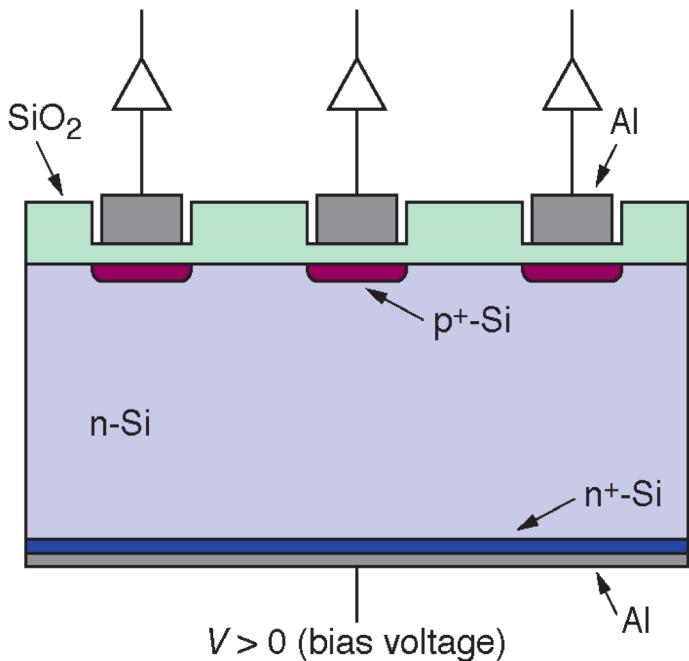


# AC coupled strip detector

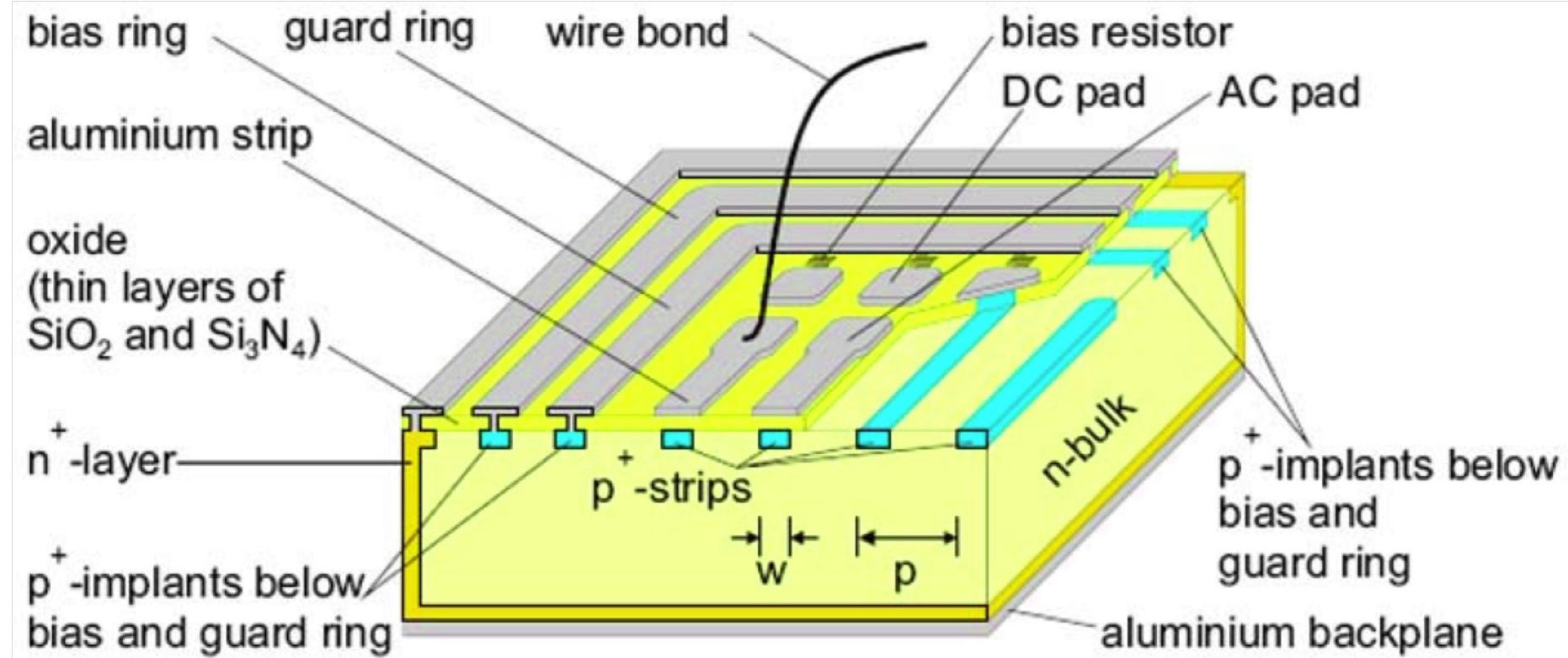
AC coupling blocks leakage current from the amplifier.

- Integration of coupling capacitances in standard planar process.
- Deposition of  $\text{SiO}_2$  with a thickness of **100–200 nm** between p+ and aluminum strip
- Increase quality of dielectric by a second layer of  $\text{Si}_3\text{N}_4$ .

AC coupled strip detector:



Most commonly used scheme using poly-Si bias resistor



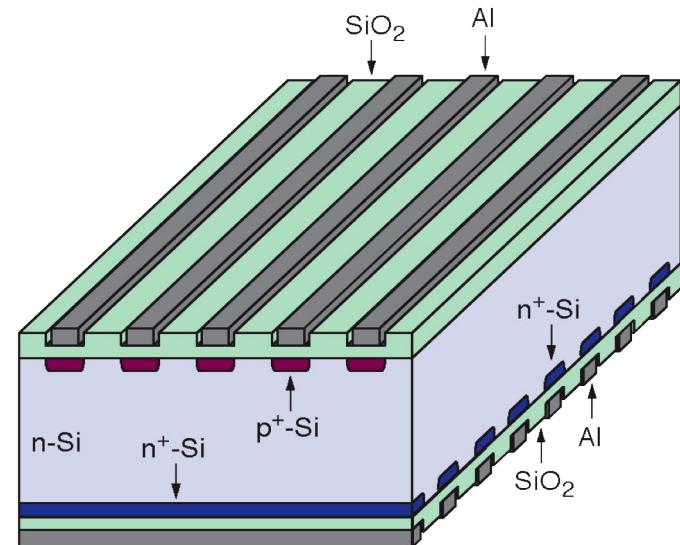
# Double Sided Silicon Detectors (DSSDs)

## Advantages:

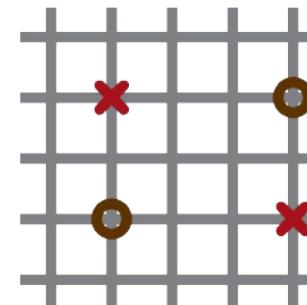
- More elegant way for measuring 2 coordinates
- Saves material

## Disadvantages:

- Needs special strip insulation of n-side (p-stop, p-spray techniques)
- Very complicated manufacturing and handling procedures → expensive
- Ghost hits at high occupancy



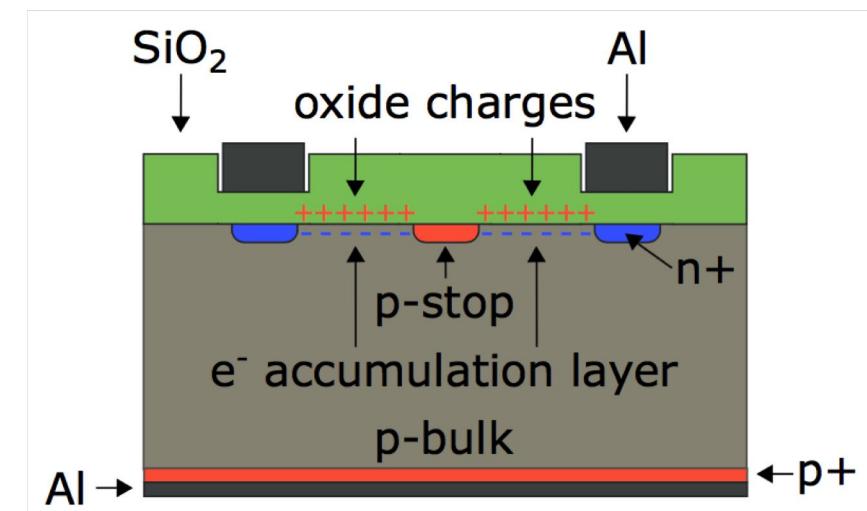
Scheme of a double sided strip detector  
(biasing structures not shown)



✗ real hits  
○ "Ghosts"

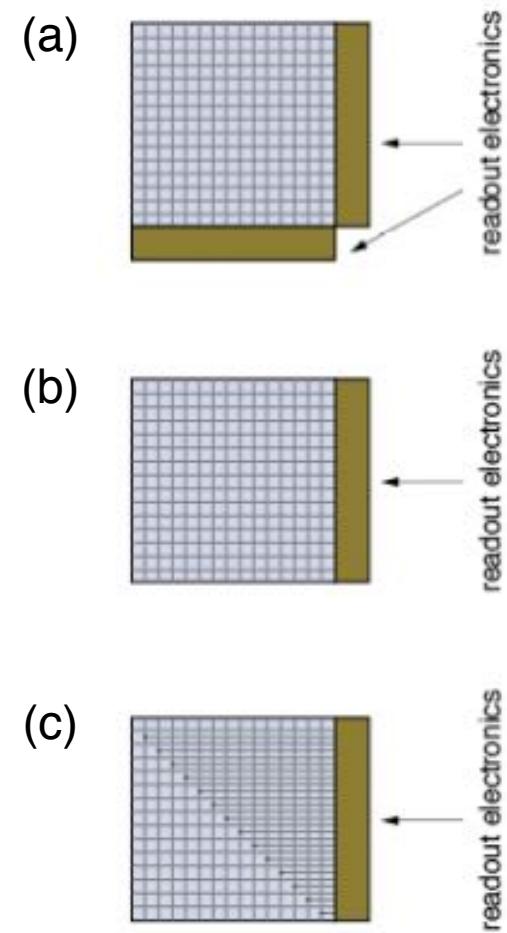
# Strip Isolation in single-sided p-type detector

- Single-sided detector using p-type substrate and n-type strips would NOT give working detector.
  - Fixed oxide charges are always positive and create e- accumulation layer in silicon
  - Electrons create short between
- For tradition and production reasons most detectors used are n-type detectors. p-type detectors have some advantages in high radiation environment (see later).



# Routing using 2<sup>nd</sup> metal layer

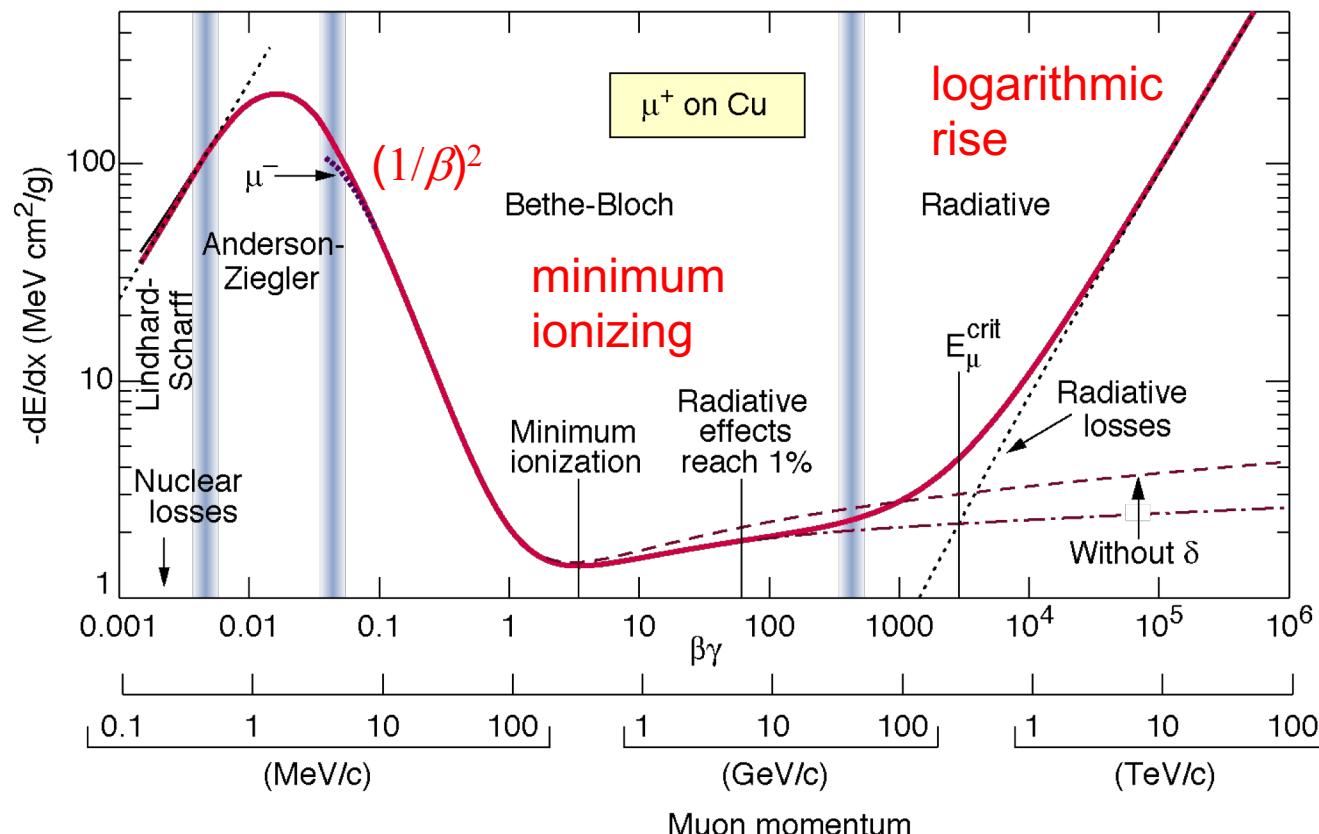
- In the case of double sided strip detectors with orthogonal strips the readout electronics is located on at least two sides (fig. a).
- Many drawbacks for construction and material distribution, especially in collider experiments.
- Electronics only on one side is a preferred configuration (fig. b).
- Possible by introducing a second metal layer. Lines in this layer are orthogonal to strips and connect each strips with the electronics (fig. c). The second metal layer can be realized by an external printed circuit board, or better integrated into the detector.



# SIGNALS IN SILICON

# Bethe-Bloch-Equation

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



Valid only for thick absorber

Thin absorber (silicon detectors) need cut-off parameter since delta electrons carry energy away

$$-\frac{1}{\rho} \frac{dE}{dx} \approx 1,5 \frac{\text{MeV}}{\text{g cm}^{-2}}$$

# Landau Distribution in thin layers

Energy Loss in Silicon Sensors:

- $(dE/dx)_{Si} = 3.88 \text{ MeV/cm}$

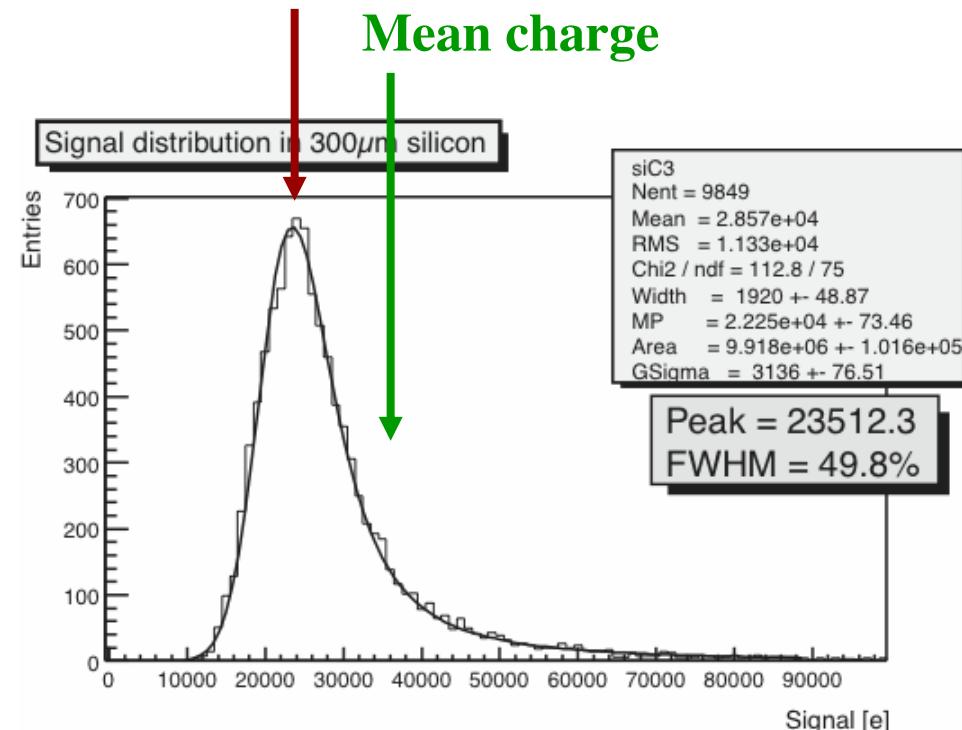
3.6eV needed to make e-h pair:

- **72 e<sup>-</sup>h /  $\mu\text{m}$  (most probable)**
- **108 e<sup>-</sup>h /  $\mu\text{m}$  (mean)**

Typical sensor thickness  
(300  $\mu\text{m}$ ):

- 21600 e<sup>-</sup> (most probable)
- 32400 e<sup>-</sup> (mean)

**Most probable charge  $\approx 0.7 \times$  mean**

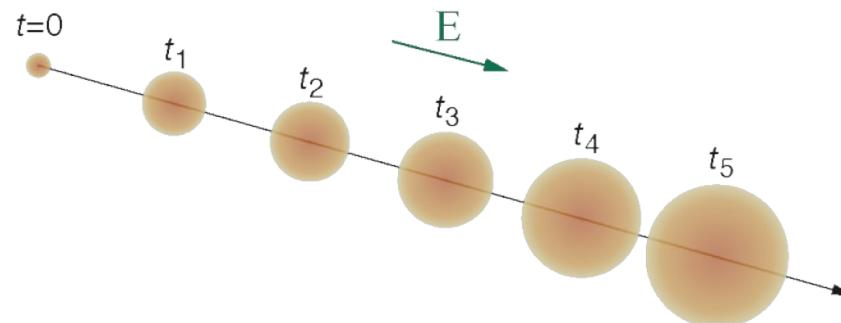


Landau distribution, convoluted with a narrow Gaussian distribution due to electronic noise and intrinsic detector fluctuations

## Diffusion (cont.)

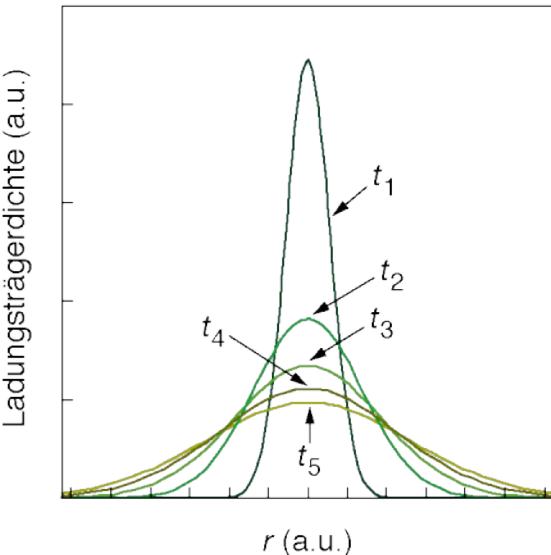
- $h^+$  created close to the anode (i.e. the  $n^+$  backplane) and  $e^-$  created close to the cathode (i.e. the  $p^+$  strips or pixels) have the longest drift path. As a consequence the diffusion acts much longer on them compared to  $e^- h^+$  with short track paths.
- The signal measured comes from many overlapping Gaussian distributions.

Drift and diffusion acts on charge carriers:



$$\sigma_D = \sqrt{2Dt} \quad \text{with:} \quad D = \frac{kT}{e} \mu$$

Charge density distribution for 5 equidistant time intervals:



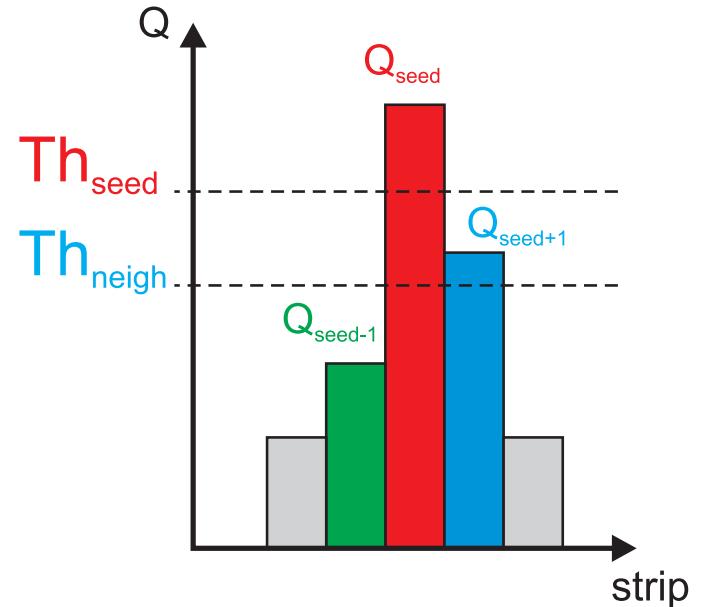
# Digital readout

- Position of hit strip
- Resolution proportional strip pitch
  - ATLAS Tracker is working in this way
- What happens when more than one strip is hit
  - Cluster

$x = \text{strip position}$

$$\sigma^2 = \frac{1}{p} \int_{-p/2}^{p/2} x^2 dx = \frac{p^2}{12}$$

$p$  ... distance between strips (readout pitch)  
 $x$  ... position of particle track



# RADIATION DAMAGE

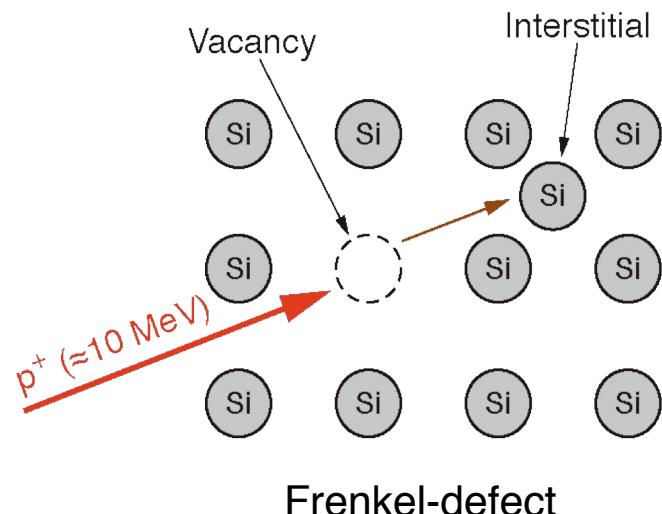
# Introduction

- **Defects** in the semiconductor lattice **create energy levels in the band gap** between valence and conduction band (see section on doping).
- Depending on the position of these energy levels the following effects will occur:
  1. **Modification of the effective doping concentration**
    - Shift of the **depletion voltage**.
    - caused by shallow energy levels (close to the band edges).
  2. **Trapping of charge carriers**
    - reduced **lifetime** of charge carriers
    - Mainly caused by deep energy levels
  3. **Easier thermal excitation of  $e^-$  and  $h^+$** 
    - increase of the **leakage current**

# Point defects

- A displaced silicon atom produces an empty space in the lattice (**Vacancy, V**) and in another place an atom in an inter lattice space (**Interstitial, I**).

A vacancy-interstitial pair is called a **Frenkel-defect**.

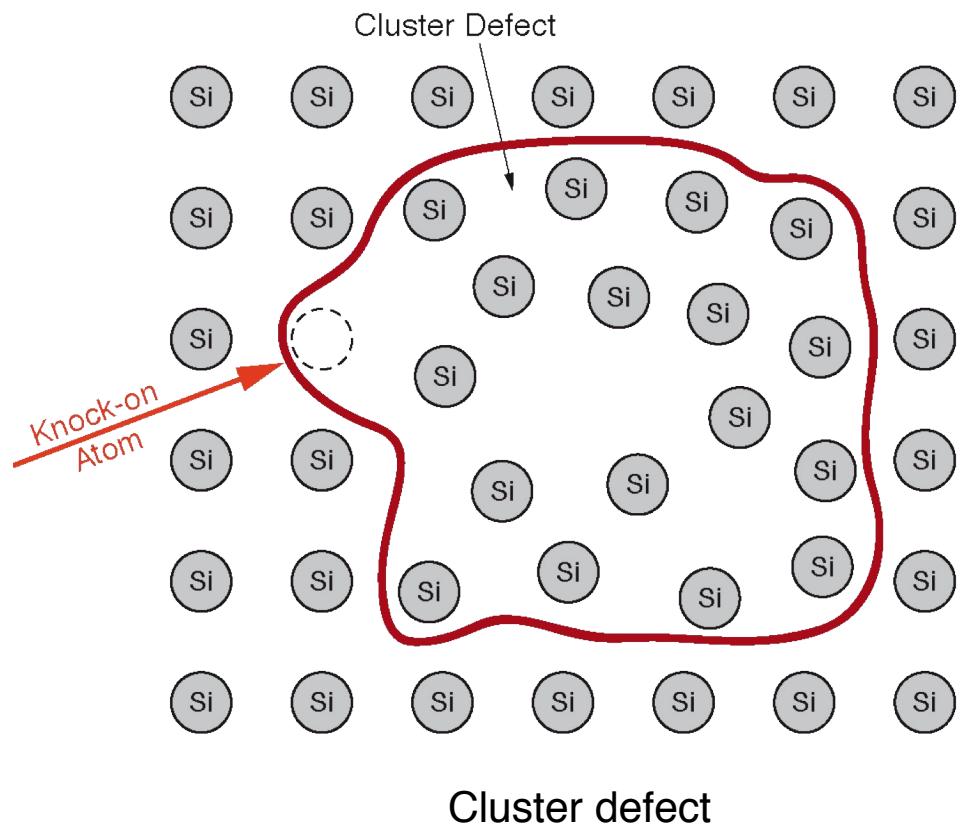


- At room temperature these defects are mobile within the lattice. An interstitial atom may drop into a vacancy and both defects disappear  
 $\Rightarrow$  **the defects anneal**.

Other defects form stable secondary defects.

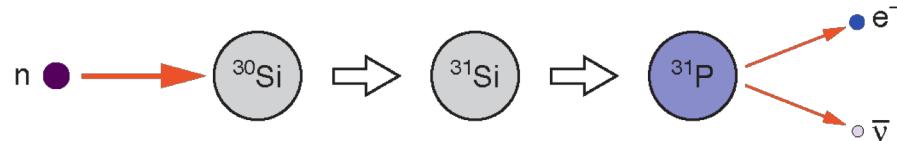
# Cluster defects

- In hard impacts the primary knock-on atom displaces additional atoms. These defects are called cluster defects.
- The size of a cluster defect is approximately 5 nm and consists of about 100 dislocated atoms.
- For high energy PKA cluster defects appear at the end of the track when the atom loses the kinetic energy and the elastic cross section increases.



# Nuclear Transformations

- Is the strong force responsible for the interaction (rather than the electromagnetic force) an atom might be transformed in another type.
- An example is the transformation of a silicon atom in a phosphor atom with the subsequent beta decay:



- If the transformed atom remains in the correct lattice position this atom acts as a regular dopant – either as donor or acceptor.

# Change of effective doping concentration

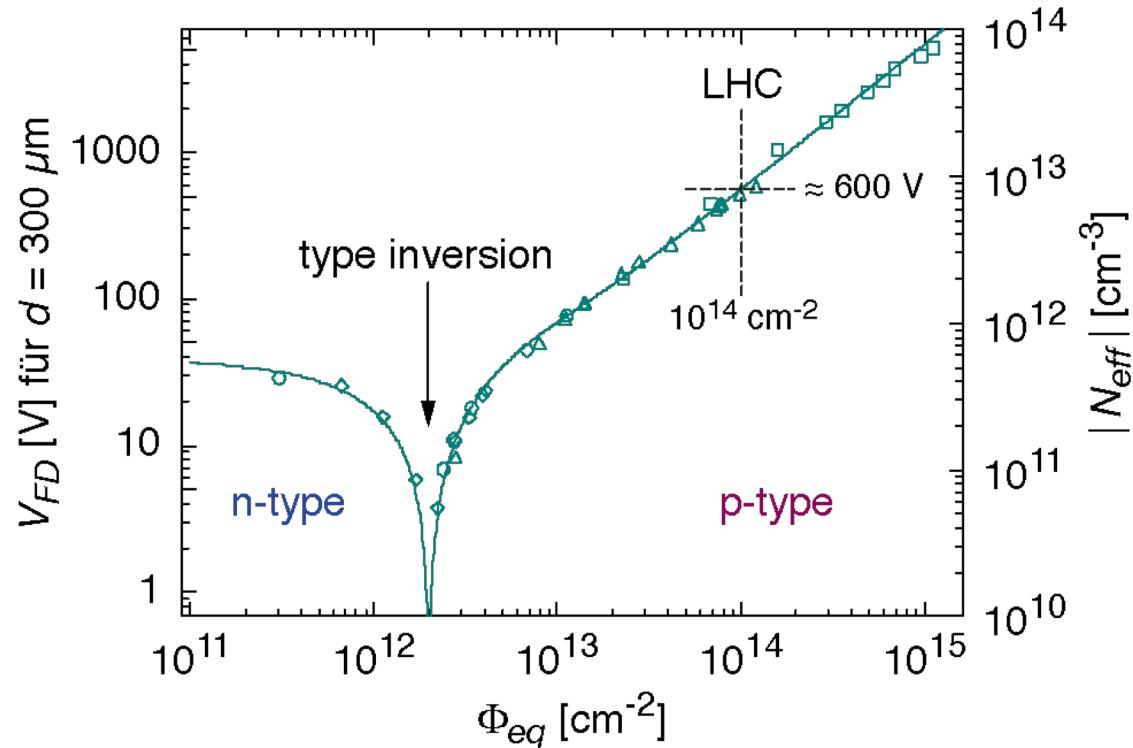
- The irradiation produces mainly acceptor like defects and removes donor type defects. In a n type silicon the effective doping concentration  $N_{eff}$  decreases and after a point called type inversion (n type Si becomes p type Si) increases again.
- The voltage needed to fully deplete the detector  $V_{FD}$  is directly related to the effective doping concentration:

$$V_{FD} \approx \frac{e}{2\epsilon_0\epsilon_r} |N_{eff}| d^2$$

- The depletion voltage and consequently the minimum operation voltage decreases, and after the inversion point increases again.

# Change of effective doping concentration (cont.)

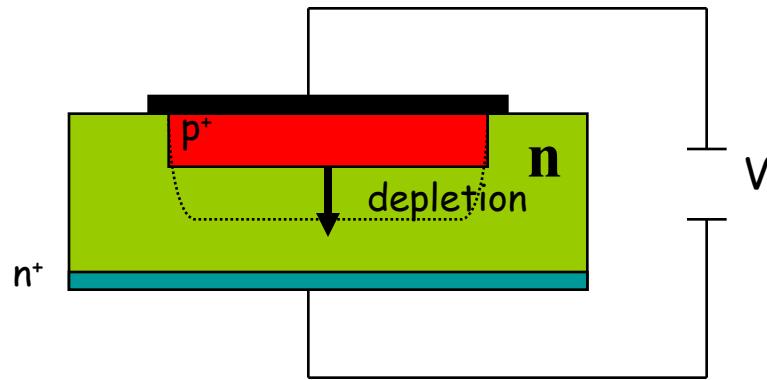
Full depletion voltage and effective doping concentration) of an originally n type silicon detector as a function of the fluence  $\Phi_{eq}$ :



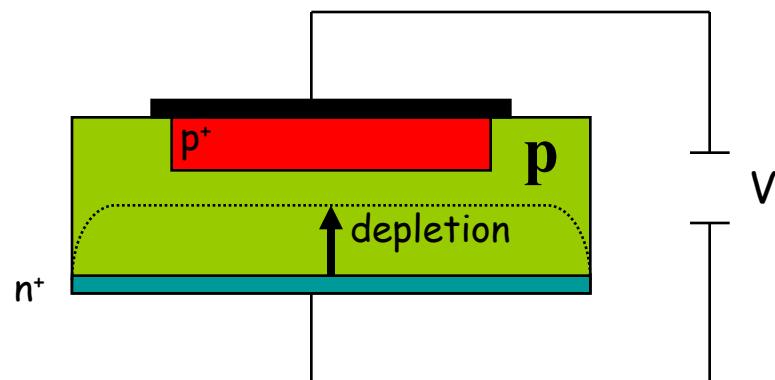
G. Lindström, *Radiation Damage in Silicon Detectors*, Nucl. Instr. Meth. A **512**, 30 (2003)

# Depletion Voltage and Type Inversion

**Before Inversion:**



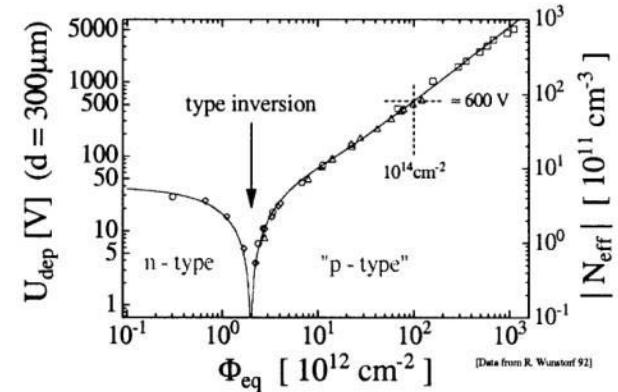
**After Inversion:**



After “inversion” of bulk-type n → p:

The depletion region grows from the back

→ Sensor does not work under-depleted anymore



## Leakage current – damage rate $\alpha$

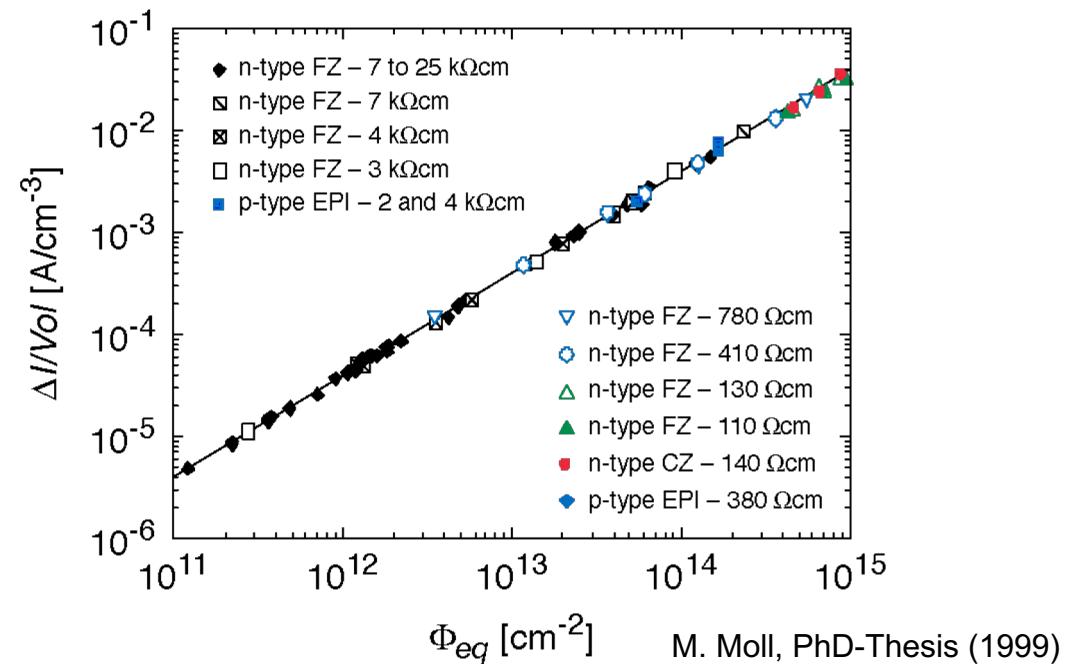
- Irradiation induced leakage current increases linear with the integrated flux:

$$\Delta I = \alpha \cdot \Phi_{eq} \cdot Vol$$

- $\alpha$  is called the **current related damage rate**. It is largely independent of the material type.  $\alpha$  depends on temperature  $\rightarrow \alpha(T)$

20° C:  $\alpha = 4,00 \cdot 10^{-17} \text{ A/m}$

-10° C:  $\alpha = 1.86 \cdot 10^{-18} \text{ A/m}$

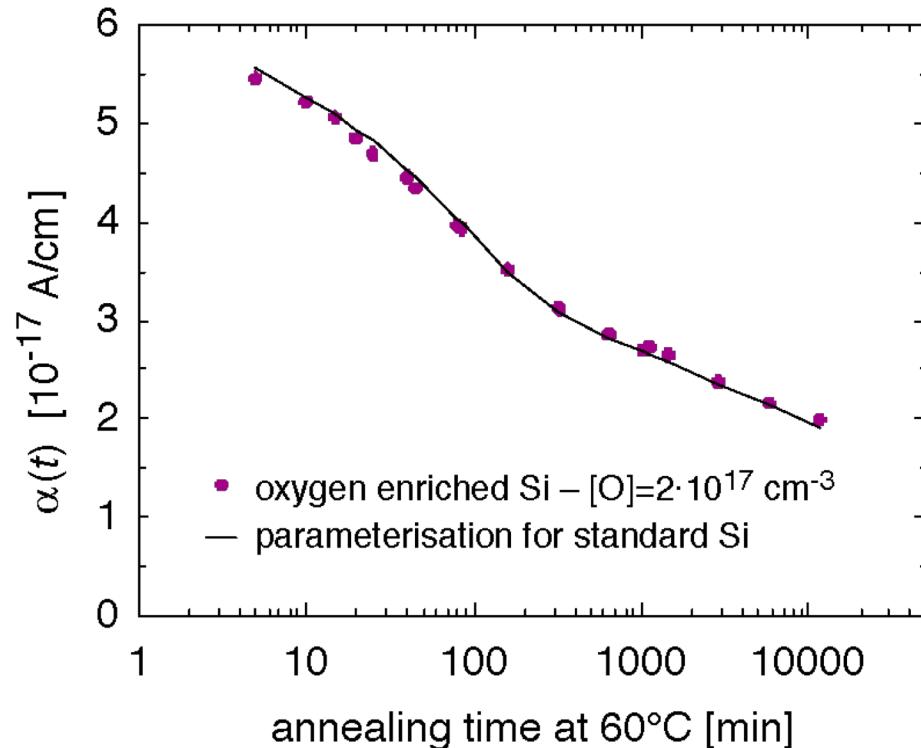


**In ten years of LHC operation the currents of the innermost layers increase by 3 orders of magnitude!**

## Leakage current – annealing

- The damage rate  $\alpha$  is time dependent.

The plot shows the development of  $\alpha$  for a detector stored at  $T = 60^\circ\text{C}$  after irradiation:



G. Lindström, *Radiation Damage in Silicon Detectors*,  
Nucl. Instr. Meth. A **512**, 30 (2003)

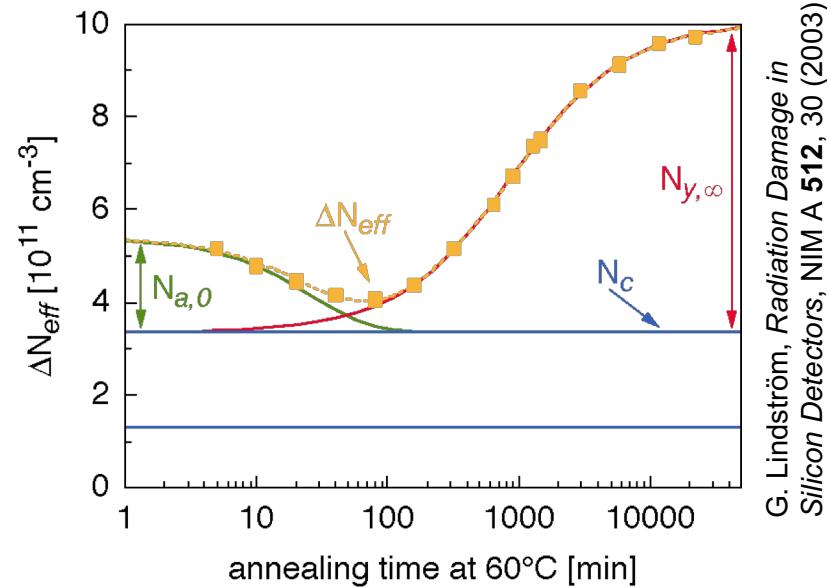
# Time Dependence of Radiation Damage

- Defects diffuse with time
- $N_{\text{eff}}$  changes:

$$\Delta N_{\text{eff}}(\Phi_{\text{eq}}, t) = \text{stable damage } (N_c(\Phi_{\text{eq}})) + \text{annealing } (N_b(\Phi_{\text{eq}}, t), N_r(\Phi_{\text{eq}}, t))$$

Three Terms:

- constant damage  $N_c$
- Two kinds of Annealing:
  - **beneficial annealing**:  $N_b$  (short-term)
  - **reverse annealing**  $N_r$  (long-term)
- Different time-scales:



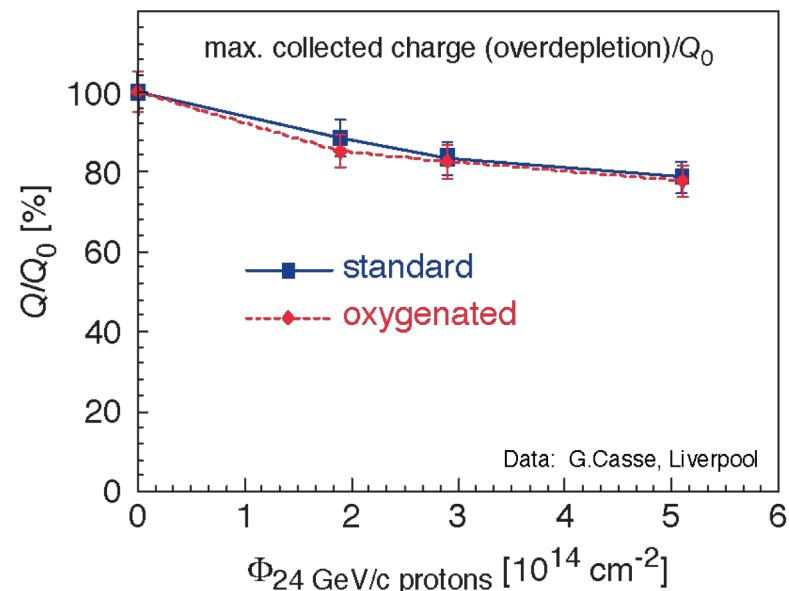
T[° C]	-10	-7	0	10	20	40	60	80
$\tau_b$	306d	180d	53d	10d	55h	4h	19min	2min

T[° C]	-10	0	10	20	40	60	80	100
$\tau_r$	516y	61y	8y	475d	17d	1260min	92min	9min

# Charge collection efficiency

- Irradiation creates defects with energy levels deep inside the band gap. These defects act as **trapping centers**. Charge carriers are trapped in these levels and released after some time (depending on the depth of the energy level).   
**charges released with delay are no longer measured within the integration time of the electronics**
  - ⇒ detector signal is reduced

Charge collection efficiency, detector irradiated with  $5 \cdot 10^{14}$  protons/cm<sup>2</sup> (24 GeV). Within the readout time of 25 ns only 80% of the signal is observed:



- Irradiated detectors operated with higher bias voltage: over-depletion
  - ⇒ can compensates partly reduced charge collection efficiency

# Surface defects – defects in the oxide

- In the amorphous oxide dislocation of atoms is not relevant. However, **ionizing radiation creates charges in the oxide**.
- Within the band gap of amorphous oxide (8.8 eV compared to 1.12 eV in Si) a large number of deep levels exist which trap charges for a long time.
- The mobility of electrons in  $\text{SiO}_2$  is much larger than the mobility of holes
  - ⇒ electrons diffuse out of the oxide, holes remain semi permanent fixed
  - ⇒ **the oxide becomes positively charged due to these fixed oxide charges.**
- **Consequences for the detector:**
  - Reduced electrical separation between implants (lower inter-strip resistance)
  - Increase of inter-strip capacitance
  - Increase of detector noise
  - Decrease of position resolution
  - Increase of surface leakage current

Silicon Detectors in High Energy Physics

# DETECTOR CHARACTERIZATION

- Measurement techniques
  - Electrically
  - Optically
  - Mechanically
- Construction of Detector Modules
  - Wire Bonding
- Beam Tests
  - Active operation with particles
  - Beam telescope

# Electrical parameters



- Typical Setup at HEPHY Vienna
  - Light-tight box
  - Instruments
  - Computer running NI Labview

# Instruments for electrical measurements



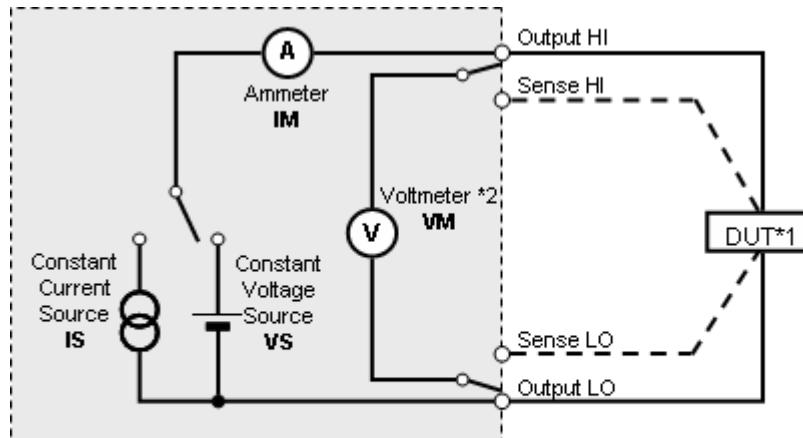
- Electrometer (precise Amp-meter)
- LCR Meter
- Source Measure Unit (SMU)

# What is a Source Measure Unit?

- Source
  - Voltage source
  - Constant current source
- Amp-meter
- Volt-meter
- in one device



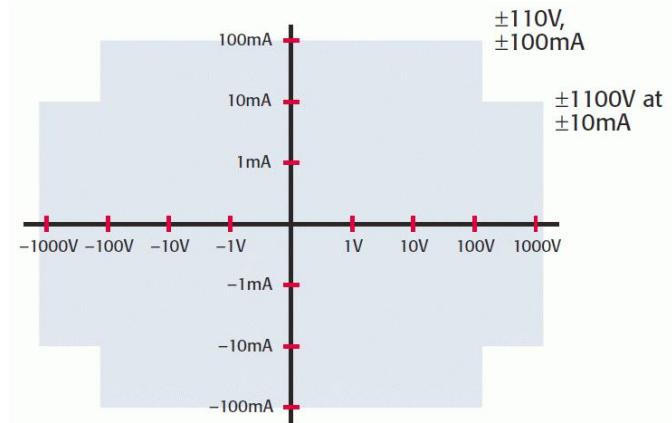
Keithley 237



GS610 construction

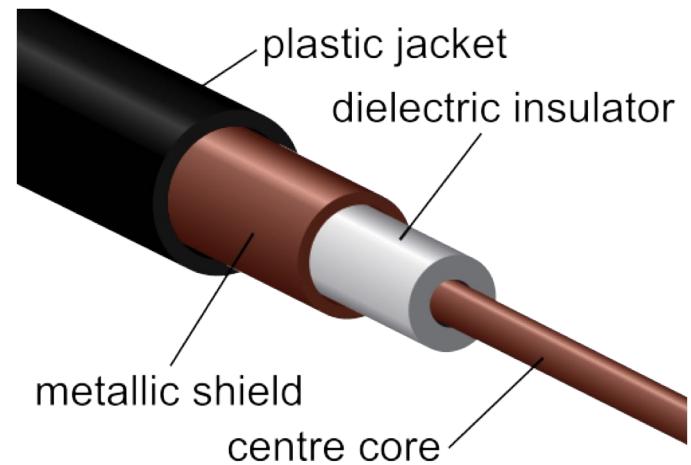
— - - four-wire system

\*1 DUT : Device Under the Test  
\*2 For DUT voltage measurement

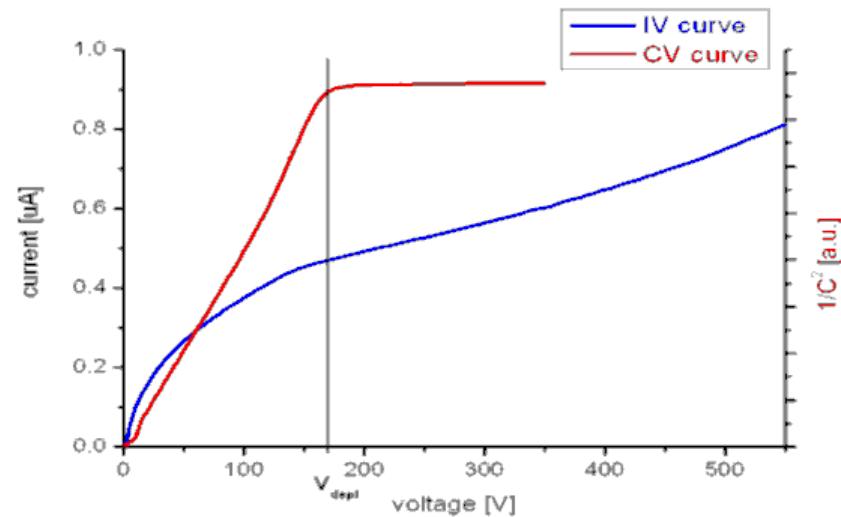


## Low noise measurements (2)

- Shielded cables necessary for whole conduction path
- Coax often sufficient
- For extreme sensitive measurements (e.g. pA):
  - Triax cables necessary



- Measurements on Silicon detectors
  - IV Curve
  - CV Curve
  - IV curves at different temperatures
- Labview
  - Writing software to make IV measurements automatically using a Source Measurement Unit



See you next week.

**THE END**