2. The ATLAS and CMS detectors

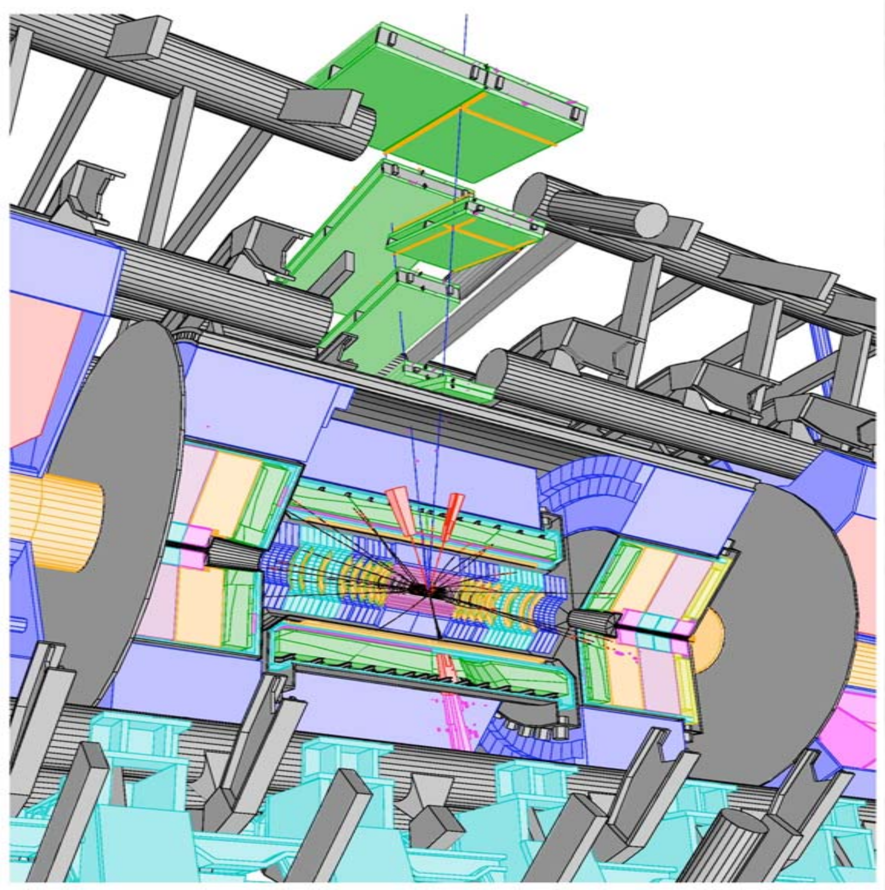
2.1 LHC detector requirements

2.2 Tracking detectors

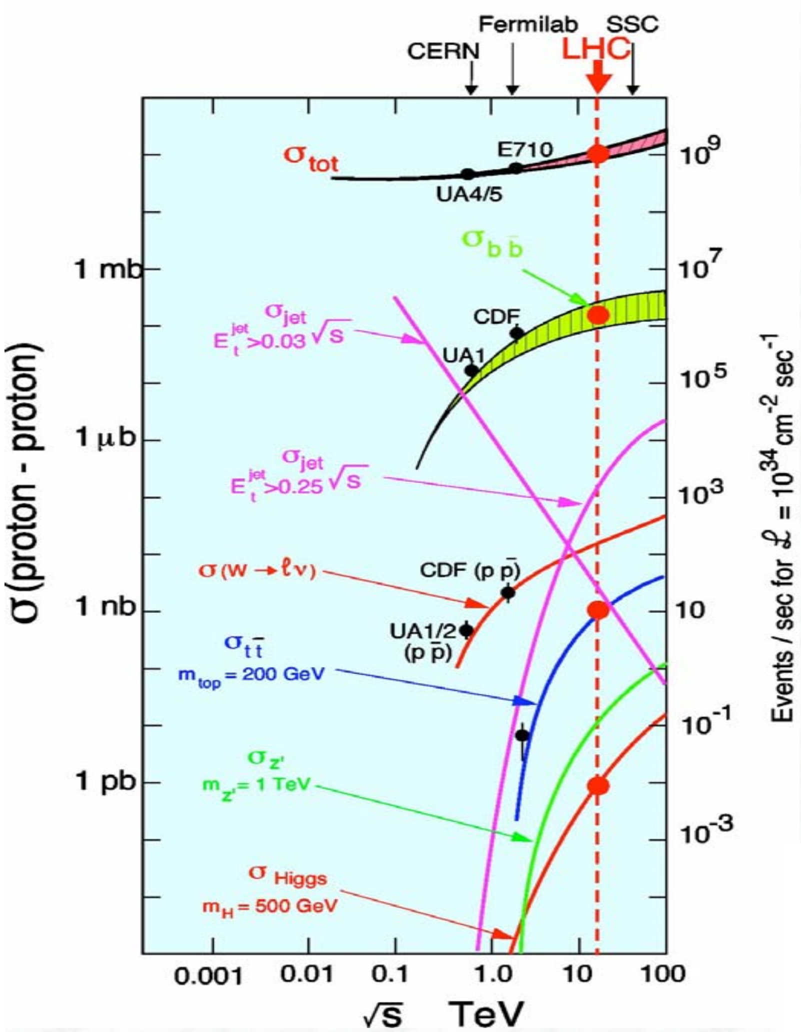
2.3 Energy measurements in calorimeters

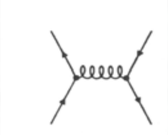
2.4 Muon detectors

2.5 Important differences between ATLAS and CMS

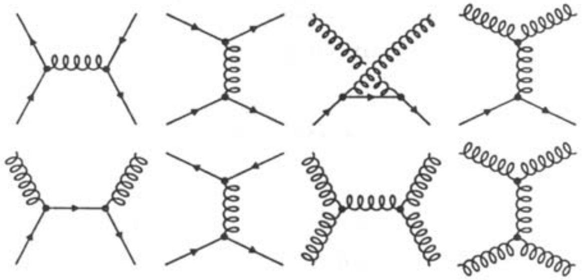


Erwartete Produktionsraten am LHC

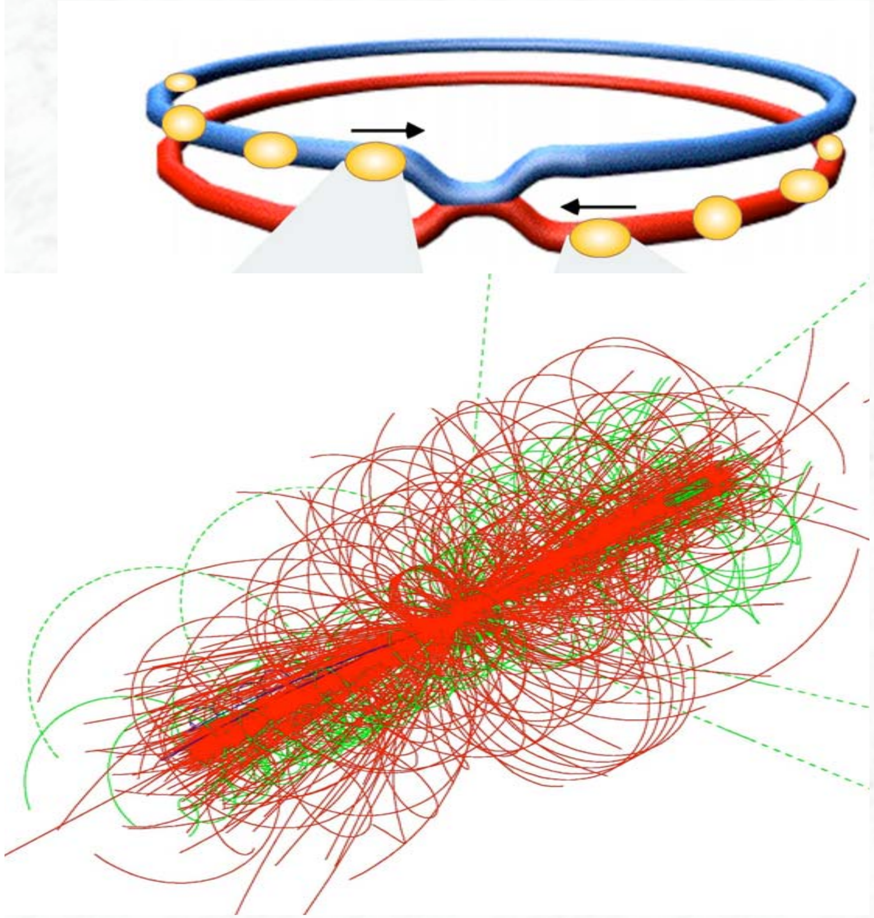


• Inelastische Proton-Proton Reaktionen:	1	Milliarde / sec
• Quark -Quark/Gluon Streuungen mit großen transversalen Impulsen	~100	Millionen/ sec
• b-Quark Paare 	5	Millionen / sec
• Top-Quark Paare	8	/ sec
• W → e ν	150	/ sec
• Z → e e	15	/ sec
• Higgs (150 GeV)	0.2	/ sec
• Gluino, Squarks (1 TeV)	0.03	/ sec

Dominante harte Streuprozesse: Quark - Quark
Quark - Gluon
Gluon - Gluon



Proton-Proton Kollisionen am LHC



Proton – Proton:

2808 x 2808 Pakete (bunches)
Separation: 7.5 m (25 ns)

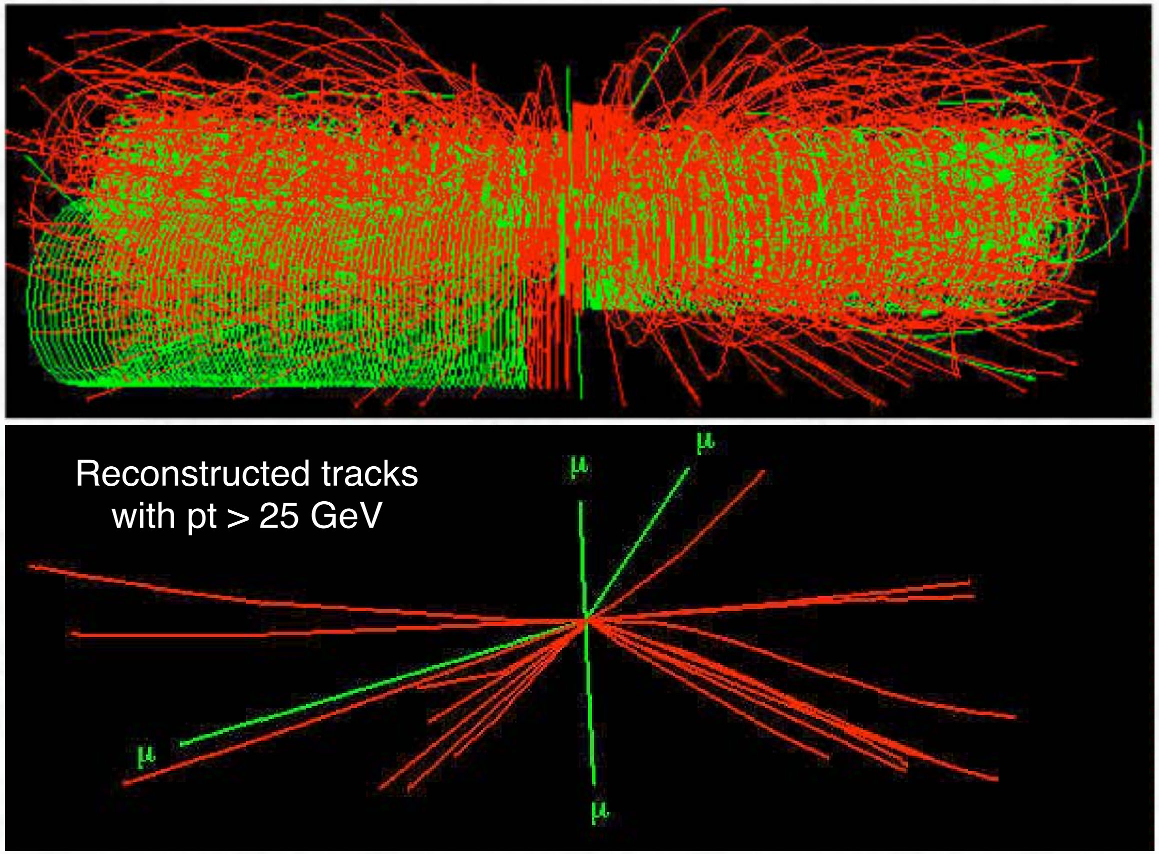
10^{11} Protonen / bunch
Kreuzungsrate der p-Pakete: 40 Mio / s
Luminosität: $L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

~10^{9} pp Kollisionen / s
(Überlagerung von 23 pp-Wechselwirkungen per Strahlkreuzung: **pile-up**)

~1600 geladene Teilchen im Detektor

⇒ Hohe Teilchendichten,
hohe Anforderungen an die Detektoren

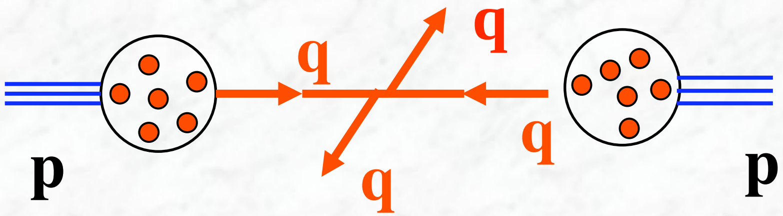
Simulation of a pp collision at the LHC: $\sqrt{s}$ = 14 TeV, L = 10^{34} cm^{-2} s^{-1}


Reconstructed tracks
with pt > 25 GeV

Reconstruction of particles with high transverse momentum reduces the number of particles drastically
(interesting object largely kept, background from soft inelastic pp collisions rejected)

What experimental signatures can be used ?

Quark-quark scattering:

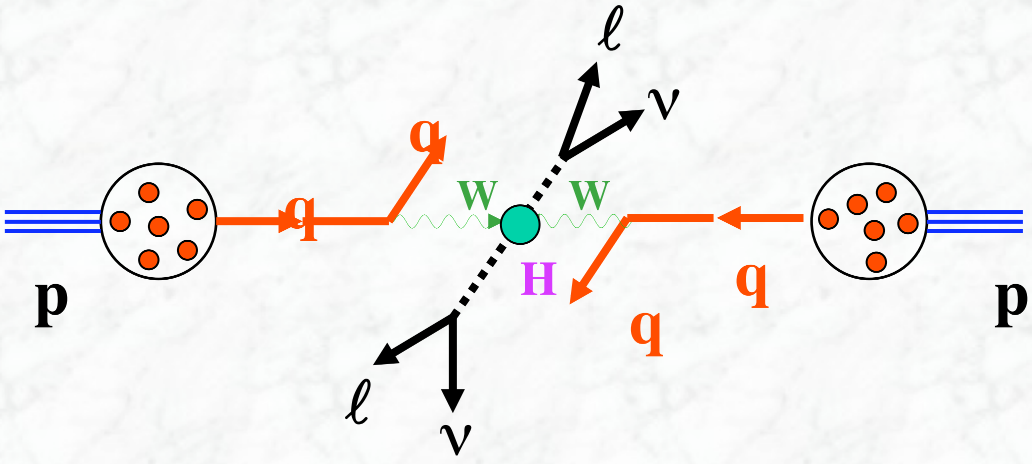


No leptons / photons in the initial and final state

If leptons with large transverse momentum are observed:

⇒ **interesting physics !**

Example: Higgs boson production and decay

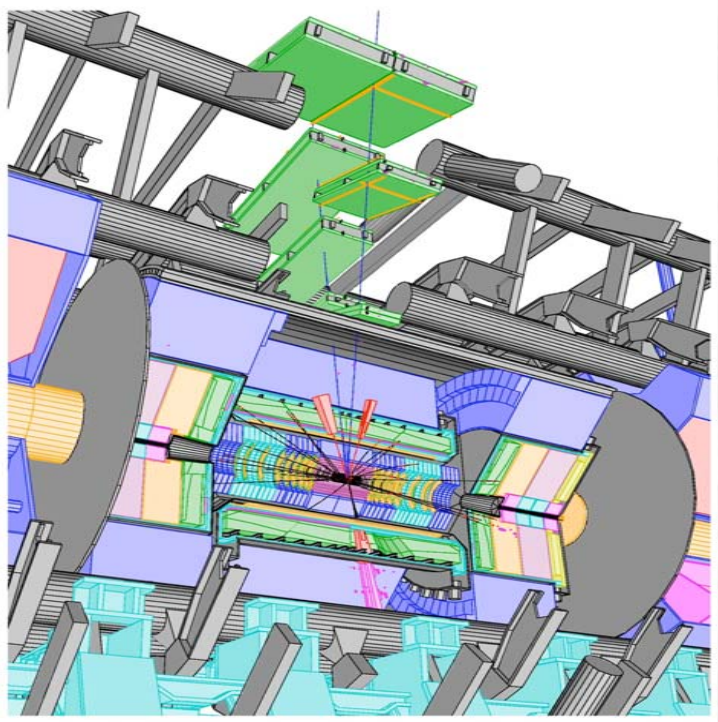


<u>Important signatures:</u>

- **Leptons und photons**
- **Missing transverse energy**

Detector requirements from physics

- Good measurement of leptons (e,μ) and photons with large transverse momentum p_T



- Good measurement of missing transverse energy (E_T^{miss})

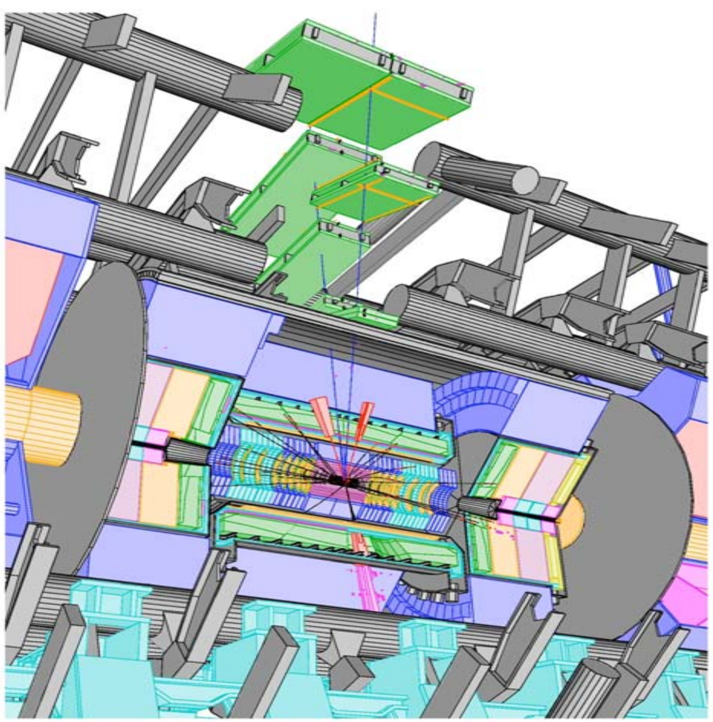
  and

  energy measurements in the forward regions

  ⇒ calorimeter coverage down to about 1 deg. to the beam pipe

- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

Detector requirements from the experimental environment (pile-up)



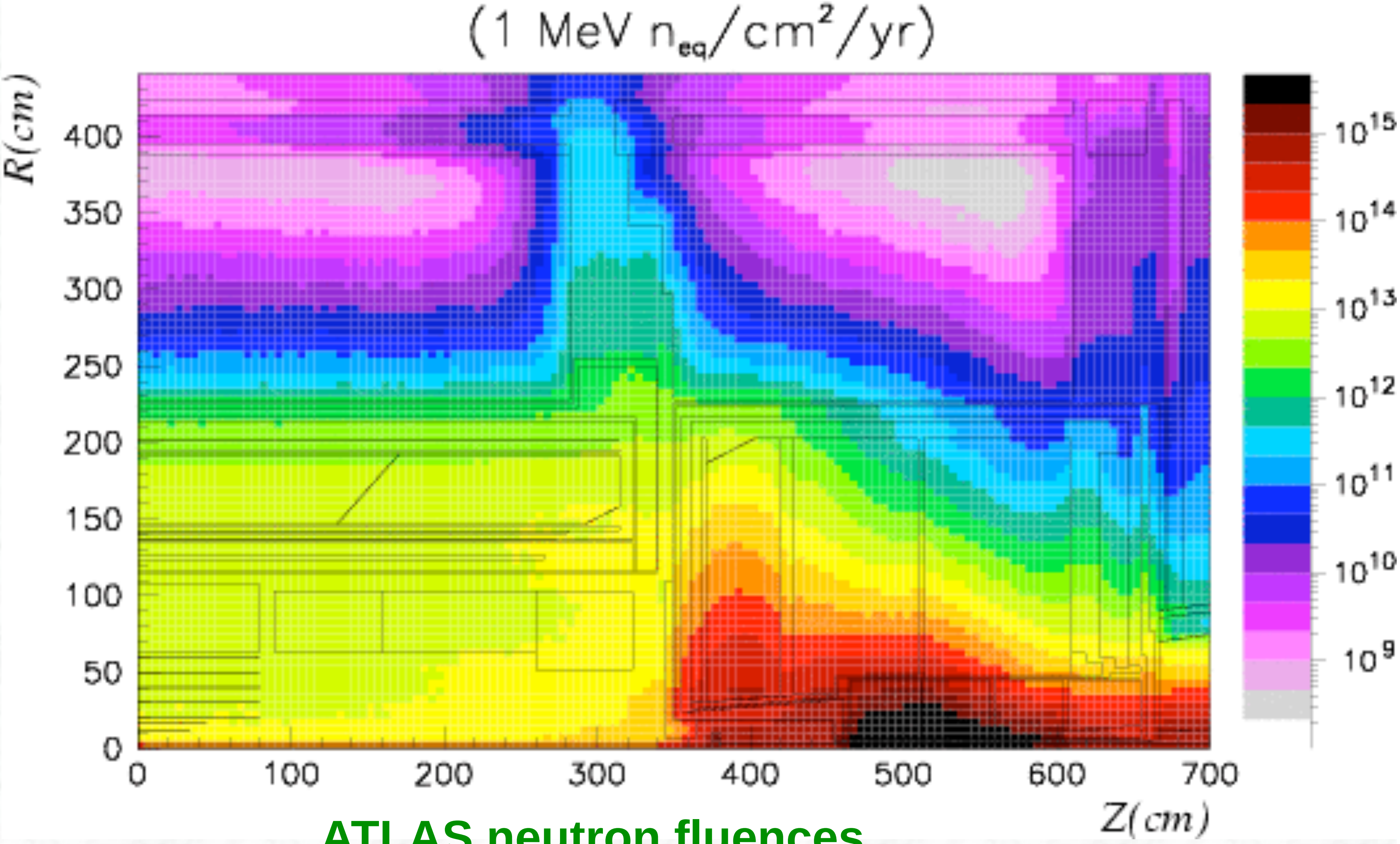
- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

  Typical response time : 20-50 ns
  → integrate over 1-2 bunch crossings
  → pile-up of 25-50 minimum bias events
  ⇒ very challenging readout electronics

- **High granularity** to minimize probability that pile-up particles be in the same detector element as interesting object
  → large number of electronic channels, high cost

- LHC detectors must be **radiation resistant**: high flux of particles from pp collisions → high radiation environment
  e.g. in forward calorimeters: up to 10^{17} n / cm^2 in 10 years of LHC operation

Experimental environment (radiation resistance of detectors)



ATLAS neutron fluences

What parameters should be measured?

- Identification of leptons (e,μ) and photons (γ)

- Precise measurement of the lepton / photon four-vector (momentum and energy)

  Momentum measurement in a magnetic field (works for e, μ)

  Energy measurement in so-called electromagnetic calorimeters (e, γ)

- Identification and energy measurement of jets (quarks and gluons) (→ energy measurement of hadrons)

  Energy measurement in so-called hadron calorimeters (charged and neutral hadrons)

- Measurement of the vector sum of the transverse energy $(\Sigma E_x, \Sigma E_y)$; modulus = total transverse energy

  electromagnetic and hadronic calorimeter
  (energy sum over all calorimeter units / cells, both electromagnetic and hadronic calorimeter)

- Missing transverse energy: $= \; -(\Sigma E_x, \Sigma E_y)$

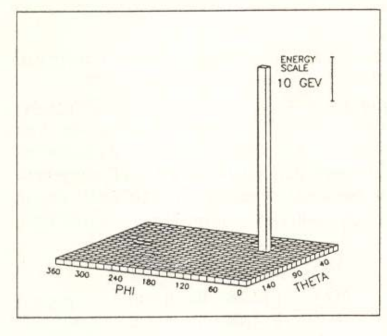
How do W and Z events look like ?

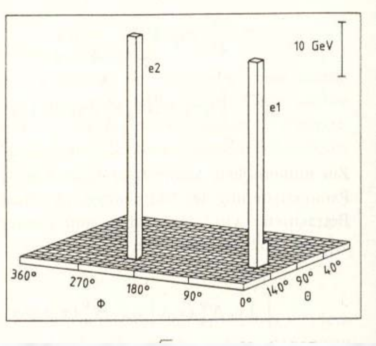
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: **$W \rightarrow \ell \nu$** (large $P_T(\ell)$, large E_T^{miss})
$Z \rightarrow \ell \ell$

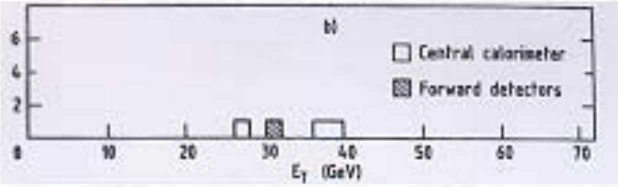
A bit of history: one of the first W events seen; UA2 experiment

W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)





Transverse momentum of the electrons



- Identification of the third generation particles (b-quarks and τ−leptons)

3rd generation particles are very important in many physics scenarios

* they are heavy → strong Higgs couplings

* appear in top-quark decays: $t \rightarrow W\,b \rightarrow l\nu\,b$

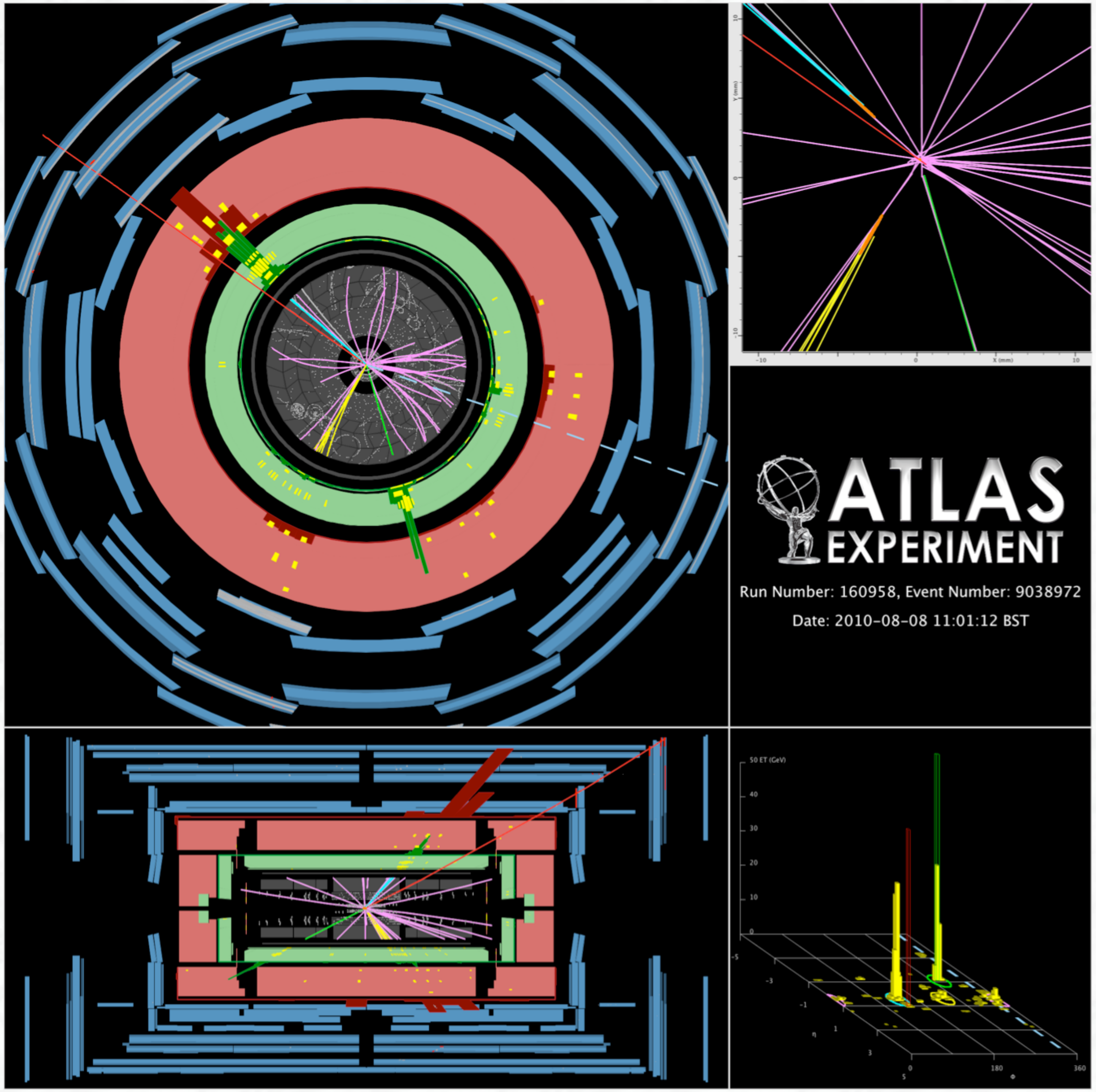
* appear in decays of SUSY particles
(the supersymmetric partners of the b- and t-quark might be the lightest squarks)

Characteristic signatures: lifetime in the order of picoseconds

τ (B-hadrons) ~1.5 ps $c\gamma\tau$ ~ 2-3 mm
τ (τ lepton) ~ 0.3 ps

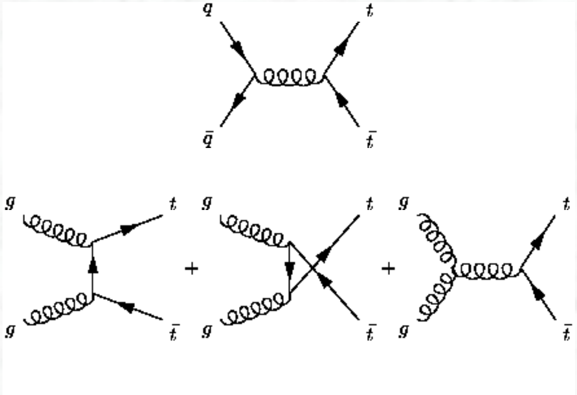
Reconstruction of the decay vertices (secondary vertices) in the vicinity of the primary vertex (interaction point)

Produktion der ersten Top-Quarks in Europa



Run Number: 160958, Event Number: 9038972

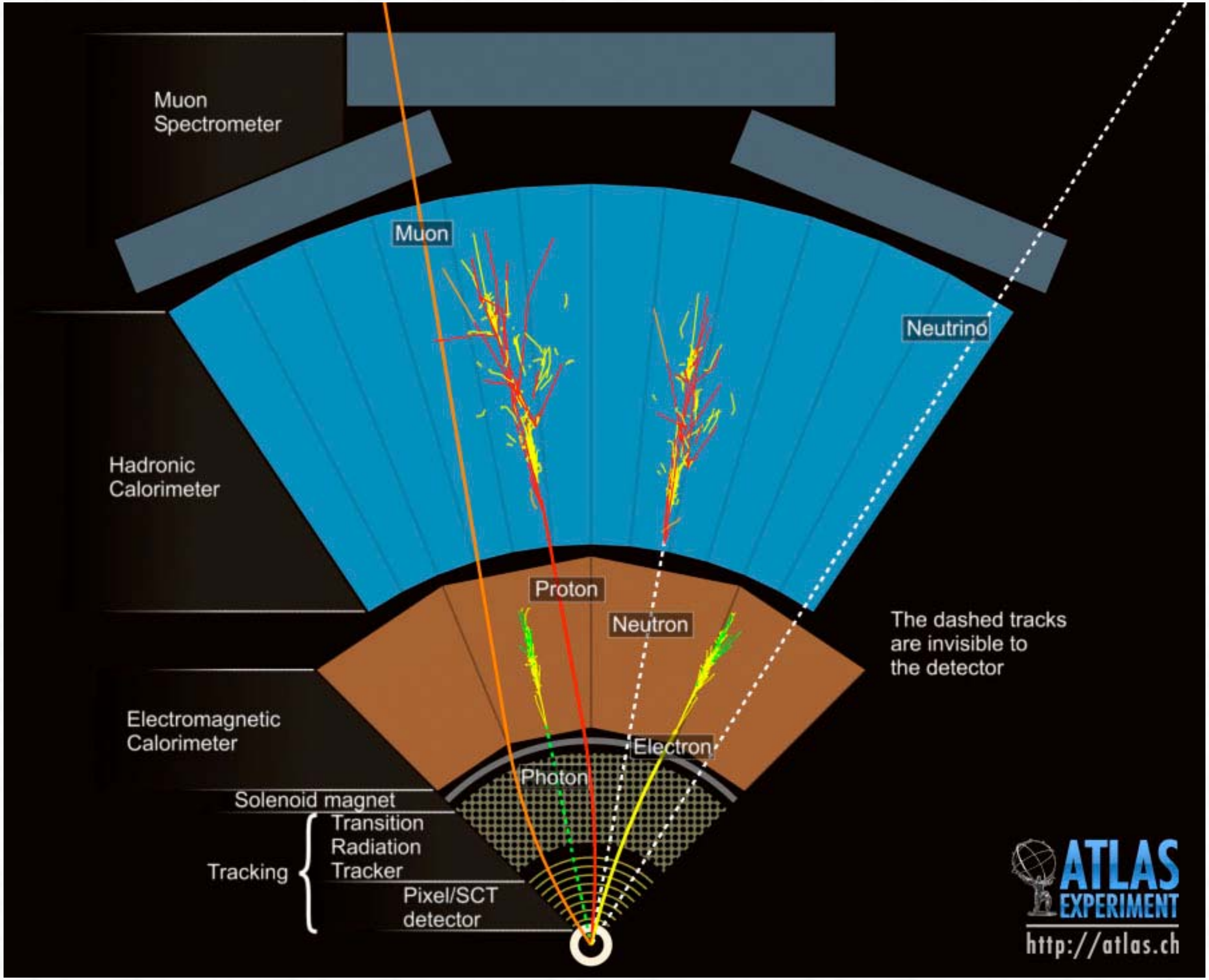
Date: 2010-08-08 11:01:12 BST



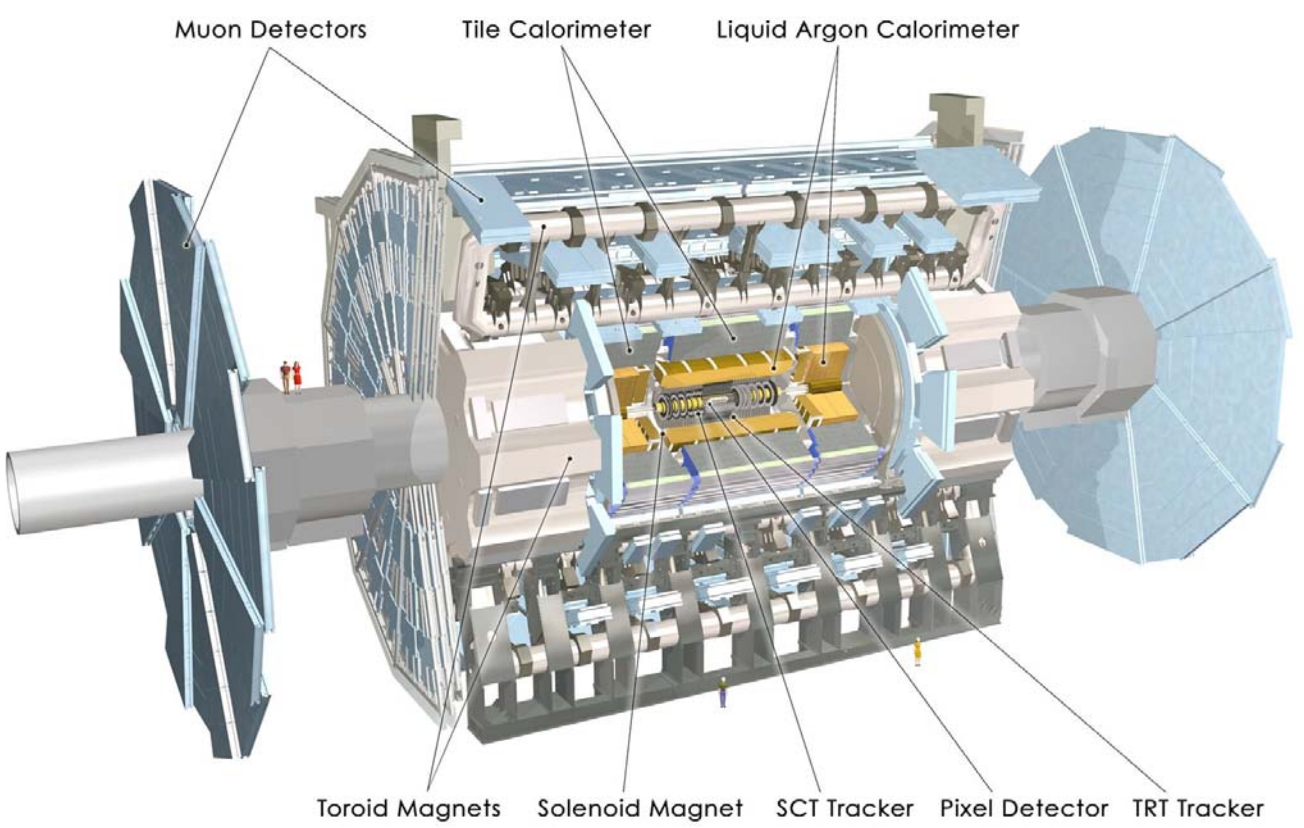
$tt \rightarrow Wb\ \ Wb \rightarrow e\nu b\ \mu\nu b$

Die Fragmentationsprodukte von b-quarks (B-Hadronen) haben eine Lebensdauer von 1.5 ps
= Flugstrecke von ~2.5 mm

Layers of the ATLAS detector



The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

  space resolution: ~ 15 μm

- Energy measurement down to 1° to the beam line

- Independent muon spectrometer (supercond. toroid system)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

2.2 Tracking (or momentum measurement) of charged particles in the inner detector

- ATLAS: magnetic field of 2 T (solenoid)

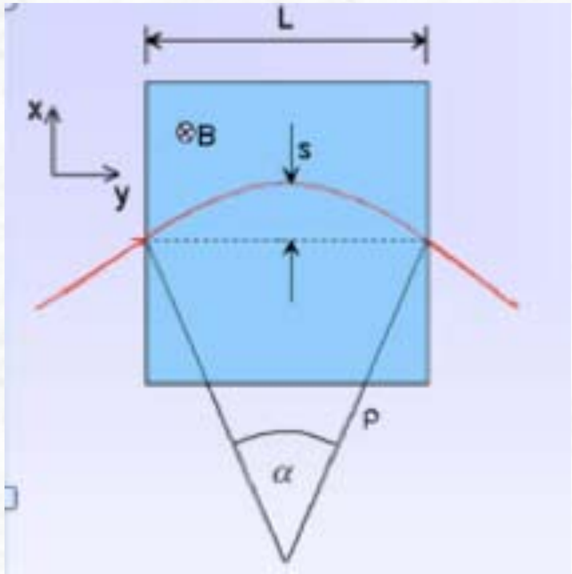
- Silicon detectors with high spatial resolution to measure the coordinates of charged particles with high precision

  Basic interaction: ionization energy loss of charged particles

- Pattern recognition (hits / coordinates → track candidates)

- Fit of curvature (3 dimensional helix model in a homogeneous magnetic field) → momentum

2.2.1 Momentum measurement



- In general the track of a charged particle is measured using several (N) position-sensitive detectors in the magnetic field volume

- Assume that each detector measures the coordinates of the track with a precision of $\sigma(x)$

- The obtainable momentum resolution depends on:
  L (length of the measurement volume)
  B (magnetic field strength)
  σ (position resolution)

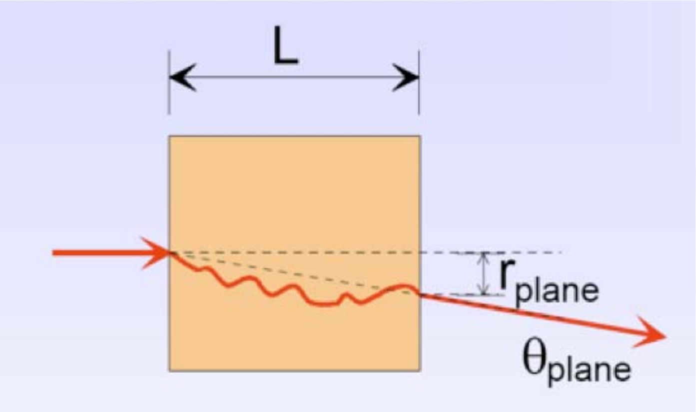
For N equidistant measurements, the momentum resolution is described by the Gluckstern formula (1963):

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for } N \geq \sim 10\text{)}$$

note: $\Delta(p_T) / p_T \sim p_T$ (relative resolution degrades with higher transverse momentum)

Momentum measurement (cont.)

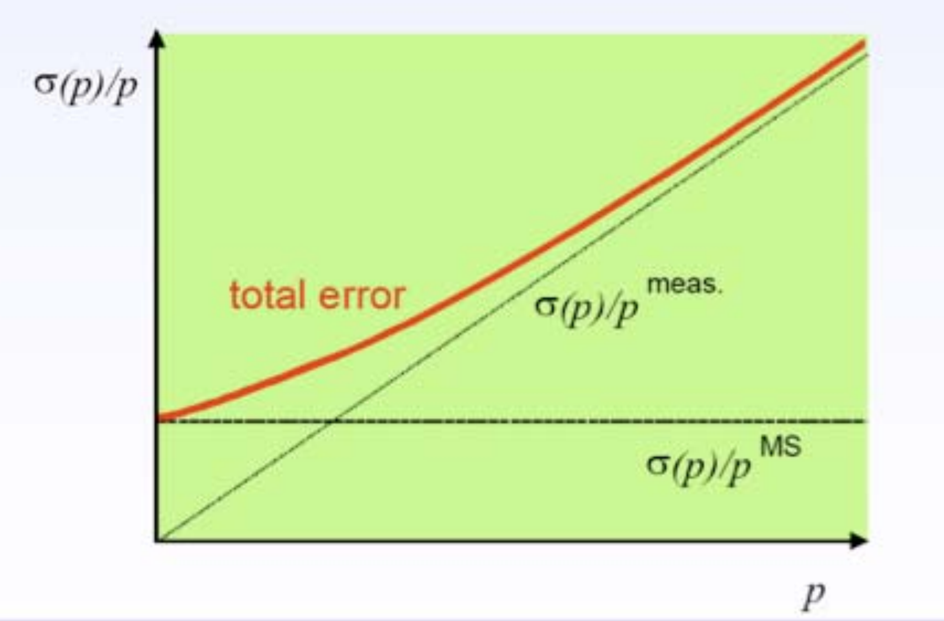
- Degradation of the resolution due to Coulomb multiple scattering (no ionization, elastic scattering on nuclei, change of direction)



$$\theta_0 = \theta^{RMS}_{plane} = \sqrt{\left\langle \theta_{plane}{}^{2} \right\rangle} = \frac{1}{\sqrt{2}}\,\theta^{RMS}_{space}$$

$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

where X_0 = radiation length of the material (characteristic parameter, see calorimeter section)



$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045\,\frac{1}{B\sqrt{LX_0}}$$

2.2.2 Ionization energy loss, Bethe-Bloch formula

geladenes Teilchen (Masse M) tritt primär in WW mit Atomelektronen

max. übertragbare Energie: $E_{kin}^{max} = \frac{2m_e p^2}{M^2+m_e^2+2m_e E/c^2} \quad \Rightarrow \quad 2m_e c^2\beta^2\gamma^2$

$\Rightarrow$ Ionisierung der Atome entlang der Teilchenbahn;
Anregung derselben in höhere Zustände

(Teilchenbahn wird durch WW mit Elektronen nur geringfügig beeinträchtigt)

Energieverlust pro Wegstrecke: $-\frac{dE}{dx}\Big|_{ion} = n_{ion} \cdot < I >$

wobei:
E : kinetische Energie
n_{ion} : Zahl der e-Ion Paare (pro Wegstrecke)
$< I >$: durchschnittliche, zur Ionisation benötigte Energie (materialabhängig)

$\frac{dE}{dx}$ wurde erstmals von H.Bethe und F.Bloch berechnet (1932)
(elektromagnetische WW, relativistische Korrekturen)

Ionisation energy loss

Annahmen:

- Masse M des einlaufenden Teilchens ist groß im Vergleich zur Elektronmasse ($M >> m_e$)
- Geschwindigkeit $v = \beta c$ ist groß geg. der Geschwindigkeit des Elektrons auf seiner Bahn ($v >> v_e$)

$$-\frac{dE}{dx} = 4\pi \frac{e^2 N_L}{m_e c^2} \; \rho \frac{Z}{A} \; \frac{Q^2}{\beta^2} \left[\ln \left(\frac{2 m_e \beta^2 c^2}{< I >} \gamma^2 \right) - \beta^2 - \frac{\delta}{2} \right]$$

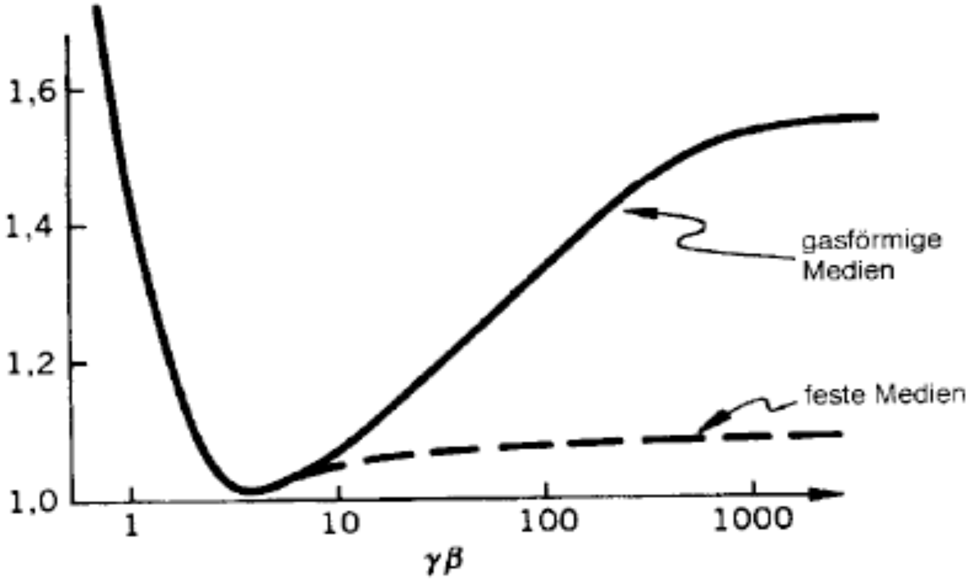
wobei:
m_e : Ruhemasse des Elektrons
N_L : Loschmidt-Zahl (Anzahl der Atome pro Grammatom)
ρ, Z, A : Dichte, Kernladungs- und Massenzahl des Absorbers
β, γ : rel. β und γ Faktoren des Teilchens
$Q = ze$: Ladung des einfallenden Teilchens
δ - Korrekturterm, Dichte-Effekt (s.u.)
(in ursprünglicher Bethe-Bloch Formel vernachlässigt)

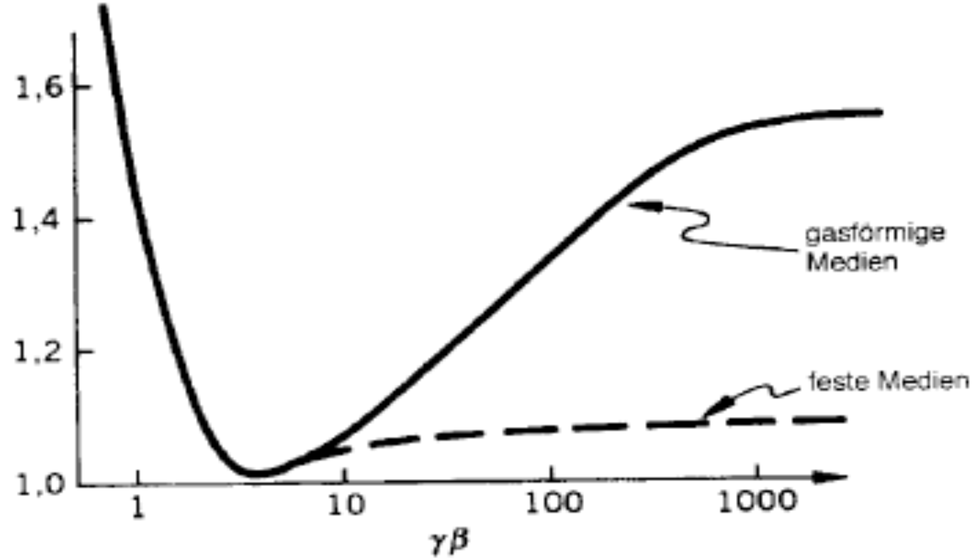
Übergang zum *Energieverlust pro Massenbelegung*,
Einheit: (MeV $\cdot cm^2$ / g)

$$\boxed{-\frac{1}{\rho}\frac{dE}{dx} = -\frac{dE}{dx'} = 4\pi\frac{e^2 N_L}{m_e c^2}\;\frac{Z}{A}\;\frac{Q^2}{\beta^2}\left[\ln\left(\frac{2 m_e \beta^2 c^2}{< I >}\gamma^2\right) - \beta^2 - \frac{\delta}{2}\right]}$$

wichtige Abhängigkeiten:

- Energieverlust ist unabhängig von der Masse des einlaufenden Teilchens
  ⇒ universelle Kurve





- hängt ab von Ladung und Geschwindigkeit des einlaufenden Teilchens $\sim Q^2/\beta^2$

- Absorber: dE/dx' ist rel. unabhängig vom Absorber; Verhältnis Z/A ist über einen großen Bereich konstant

- Minimum für $\beta\gamma \approx 4$
  minimal ionisierendes Teilchen: $\frac{dE}{dx}|_{min} \approx 1.5\ \frac{\mathrm{MeV \cdot cm^2}}{g}$

- relativ. Anstieg wird für große $\beta\gamma$ gedämpft, Sättigungseffekt, bedingt durch langreichweitige inneratomare Abschirmungseffekte (Korrekturterm δ)

  (materialabhängig, gut beobachtet in Gasen, nicht jedoch in Festkörpern)

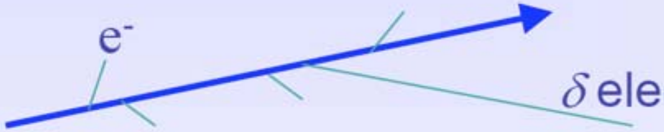
Energy loss distributions

Real detector (limited granularity) can not measure <*dE/dx*> !

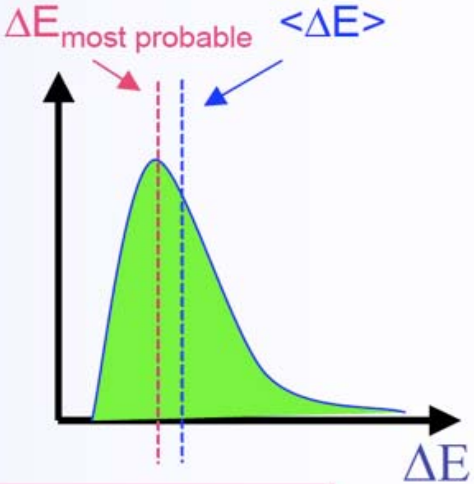
It measures the energy ΔE deposited in a layer of finite thickness δx.

For thin layers or low density materials:

→ Few collisions, some with high energy transfer.



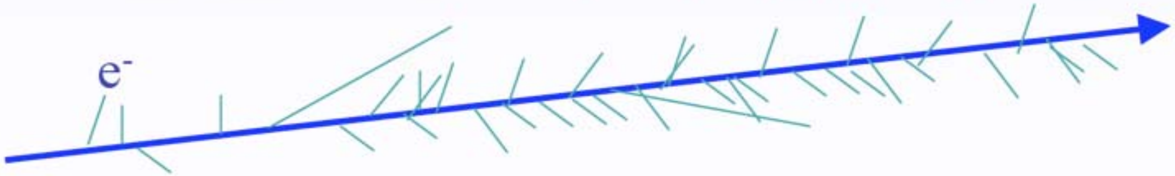
→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

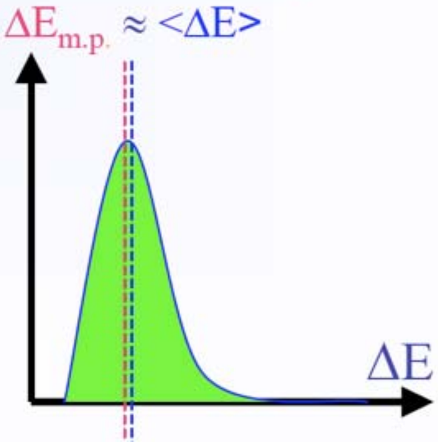


Example: Si sensor: 300 μm thick. $\Delta E_{m.p} \sim 82$ keV $<\Delta E> \sim 115$ keV

For thick layers and high density materials:

→ Many collisions.
→ Central Limit Theorem → Gaussian shaped distributions.

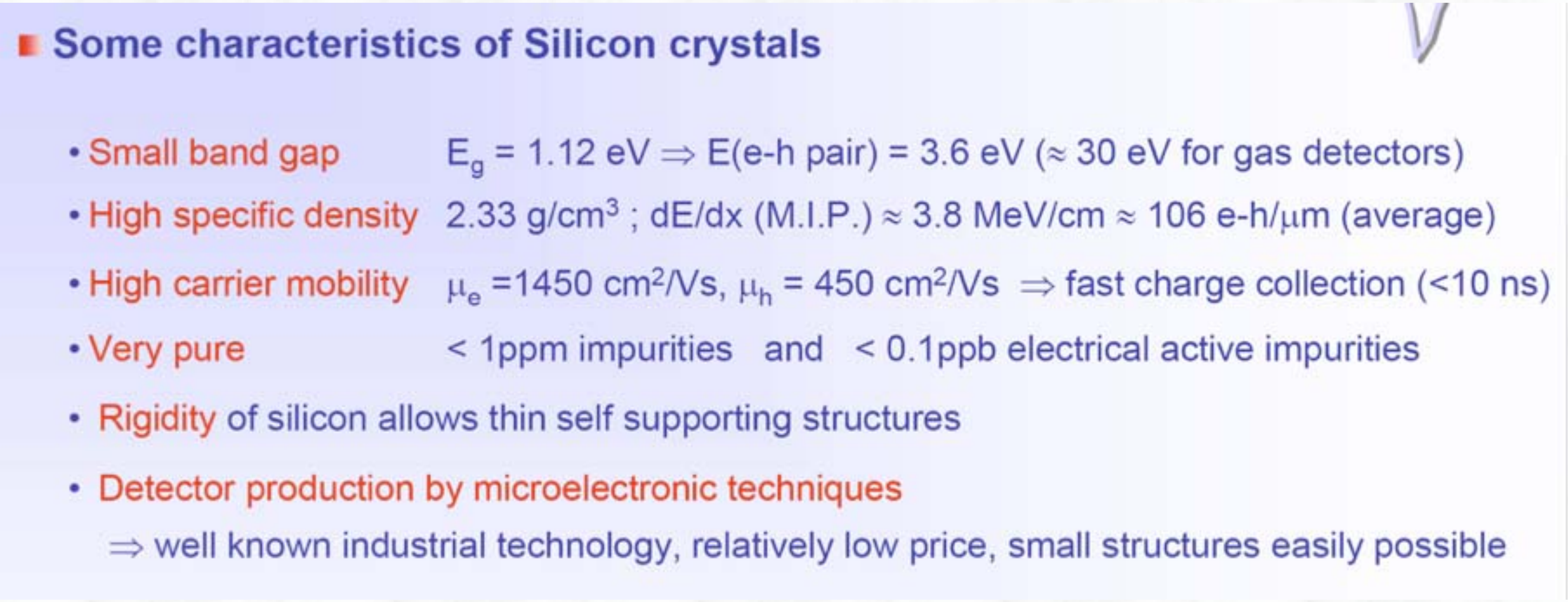




2.2.3 Semiconductor detectors (silicon)

- In all modern particle physics experiments semiconductor detectors are used as tracking devices with a high spatial resolution (15-20 μm)

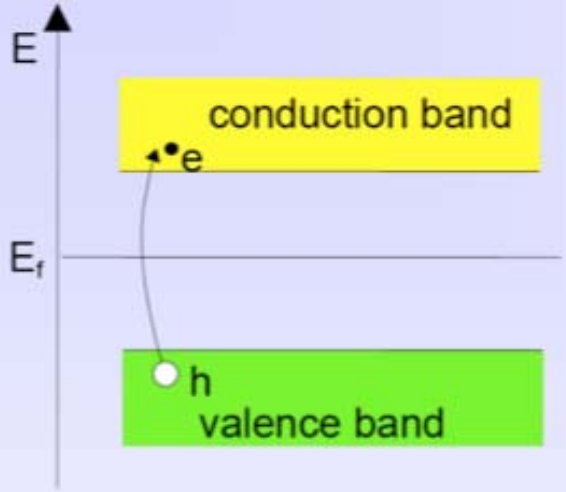
- Nearly an order of magnitude more precise than detectors based on ionisation in gas (which was standard up to LEP experiments)



Some characteristics of Silicon crystals

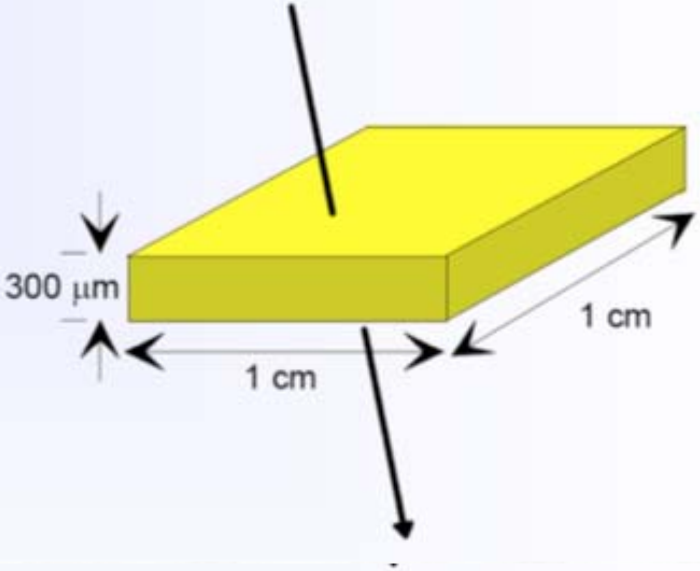
- Small band gap $E_g = 1.12$ eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
- High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
- High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
- Very pure < 1ppm impurities and < 0.1ppb electrical active impurities
- Rigidity of silicon allows thin self supporting structures
- Detector production by microelectronic techniques
  ⇒ well known industrial technology, relatively low price, small structures easily possible

How to obtain a signal



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3}

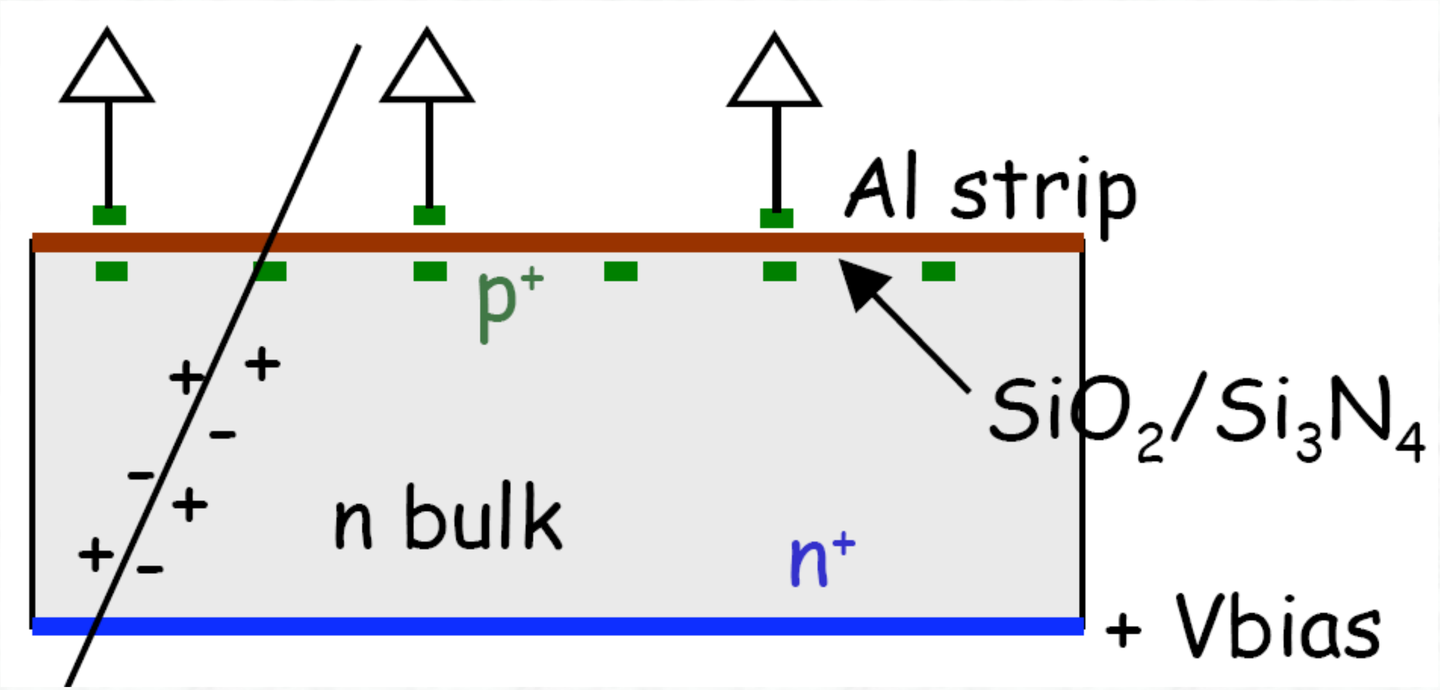


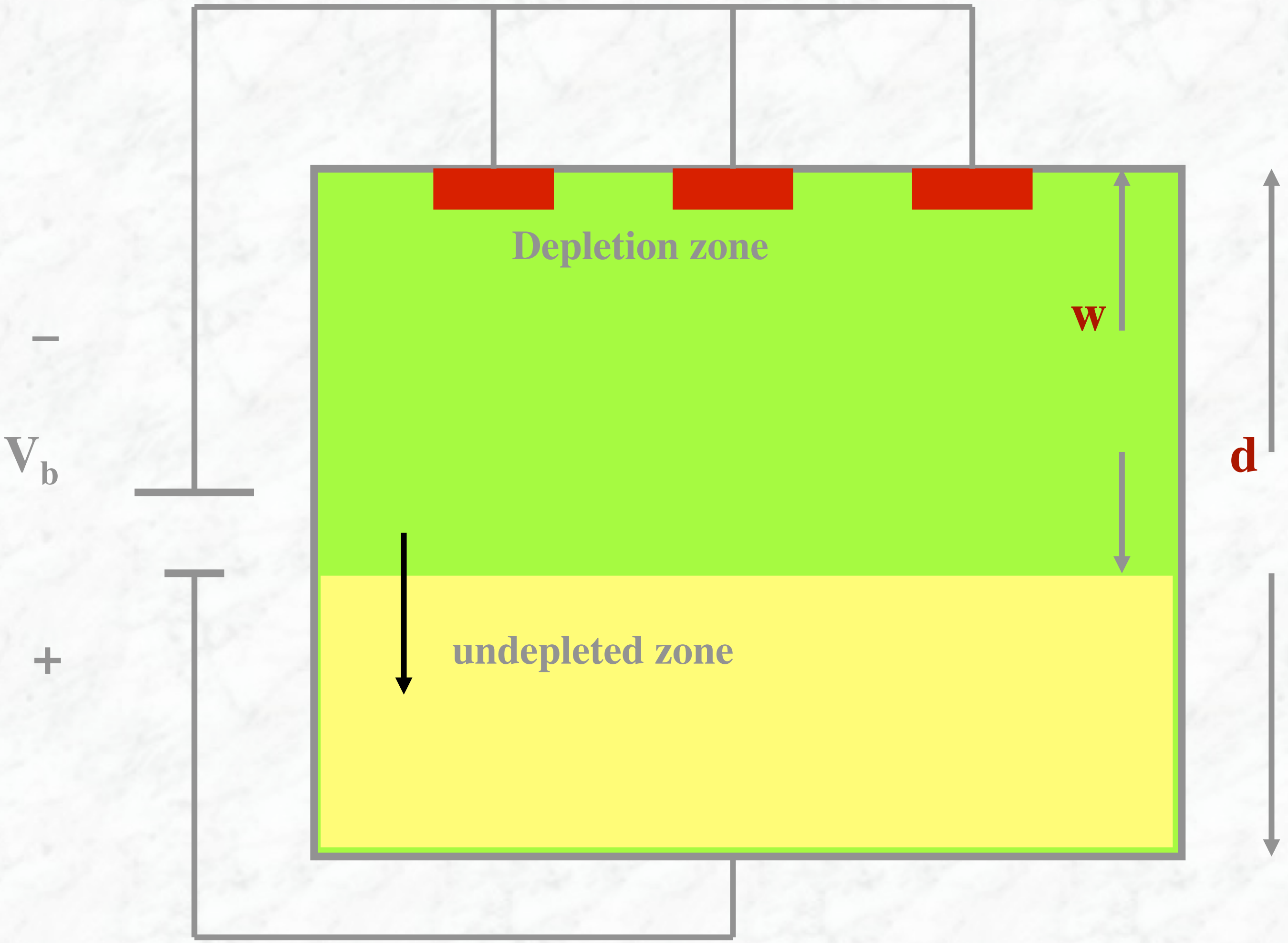
$4.5 \cdot 10^8$ free charge carriers in this volume, but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P.

⇒ Reduce number of free charge carriers, i.e. deplete the detector

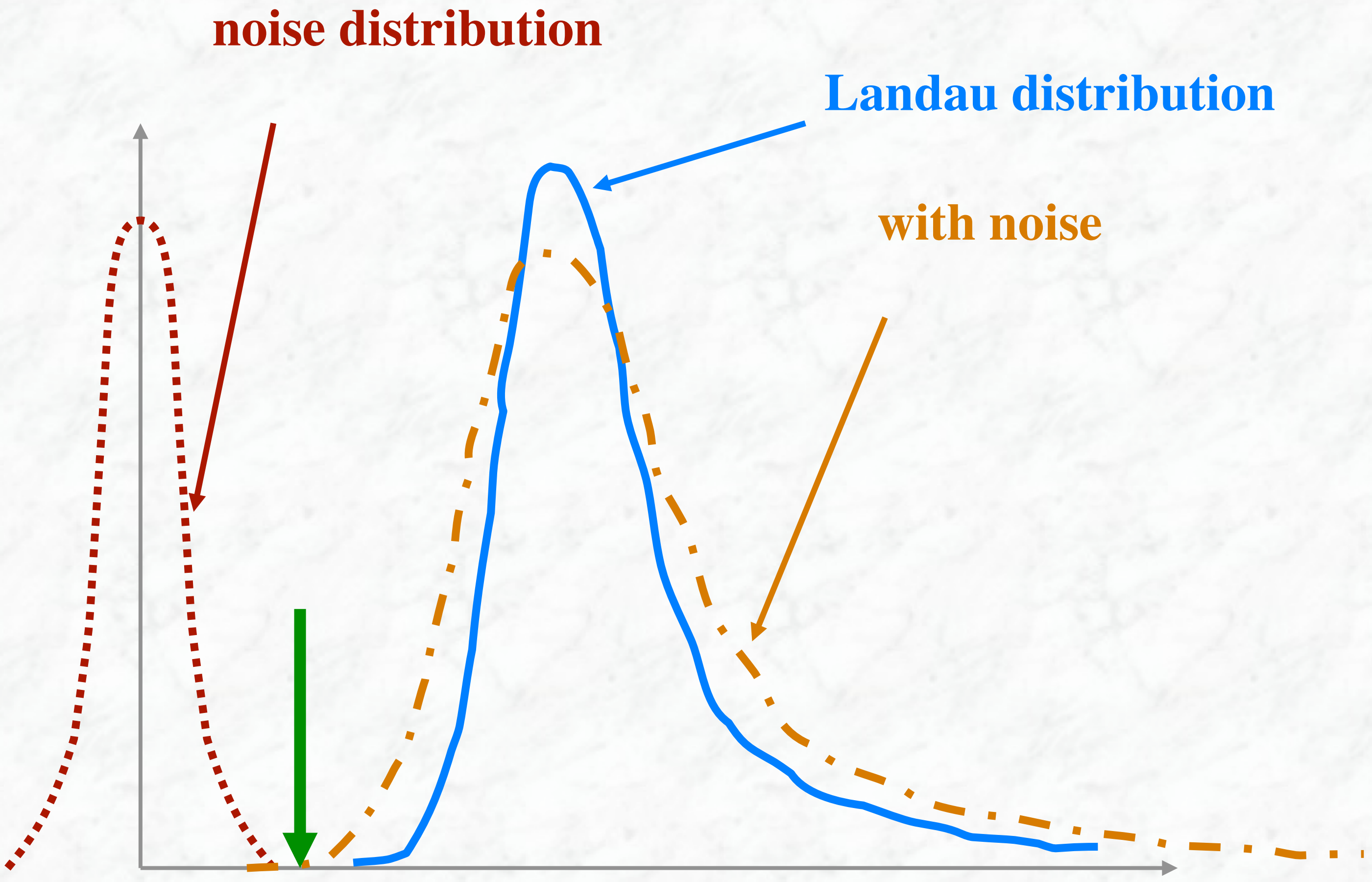
⇒ **Most detectors make use of reverse biased p-n junctions**

Schematic Si-Detector

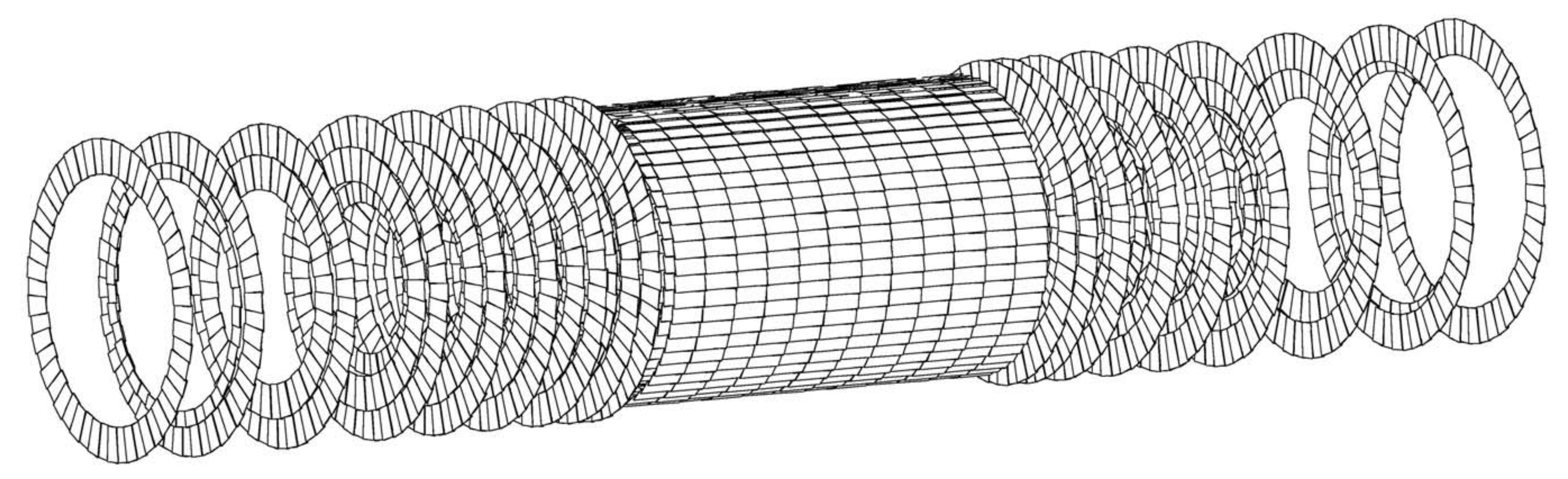



Depletion zone
w
–
V_b
d
+
undepleted zone

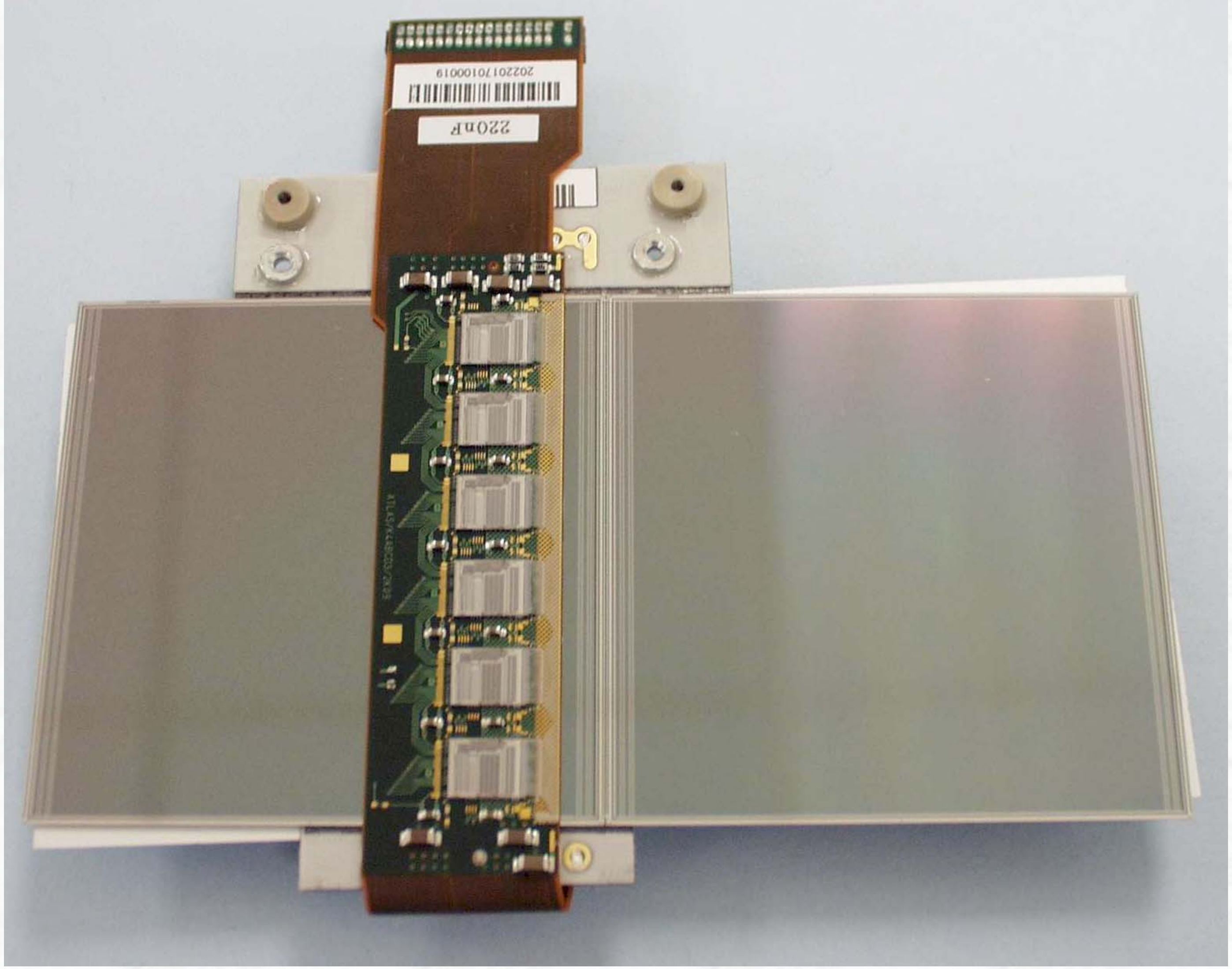
Signal, Noise and S/N Cut



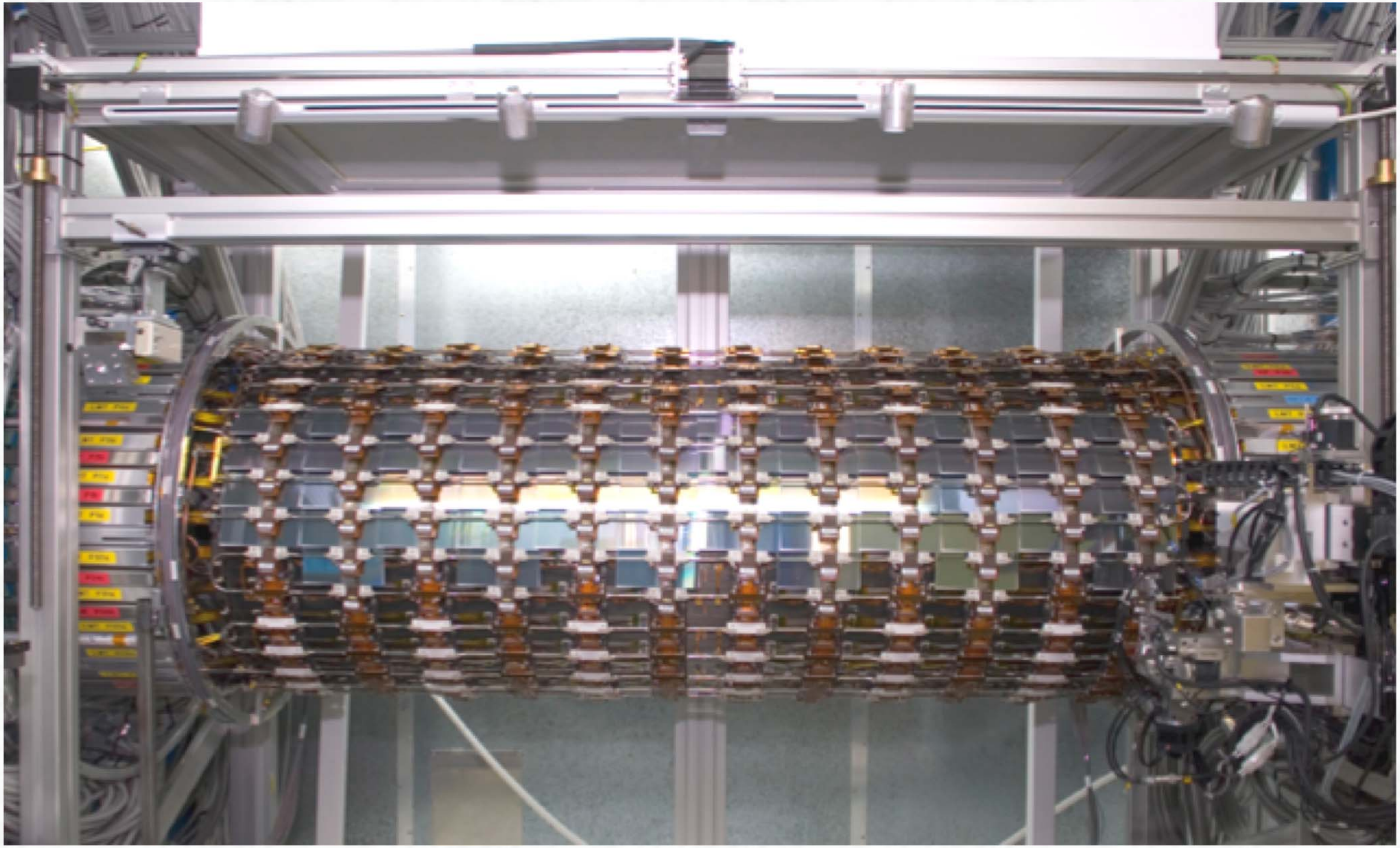
Example: ATLAS Si-Tracker SCT



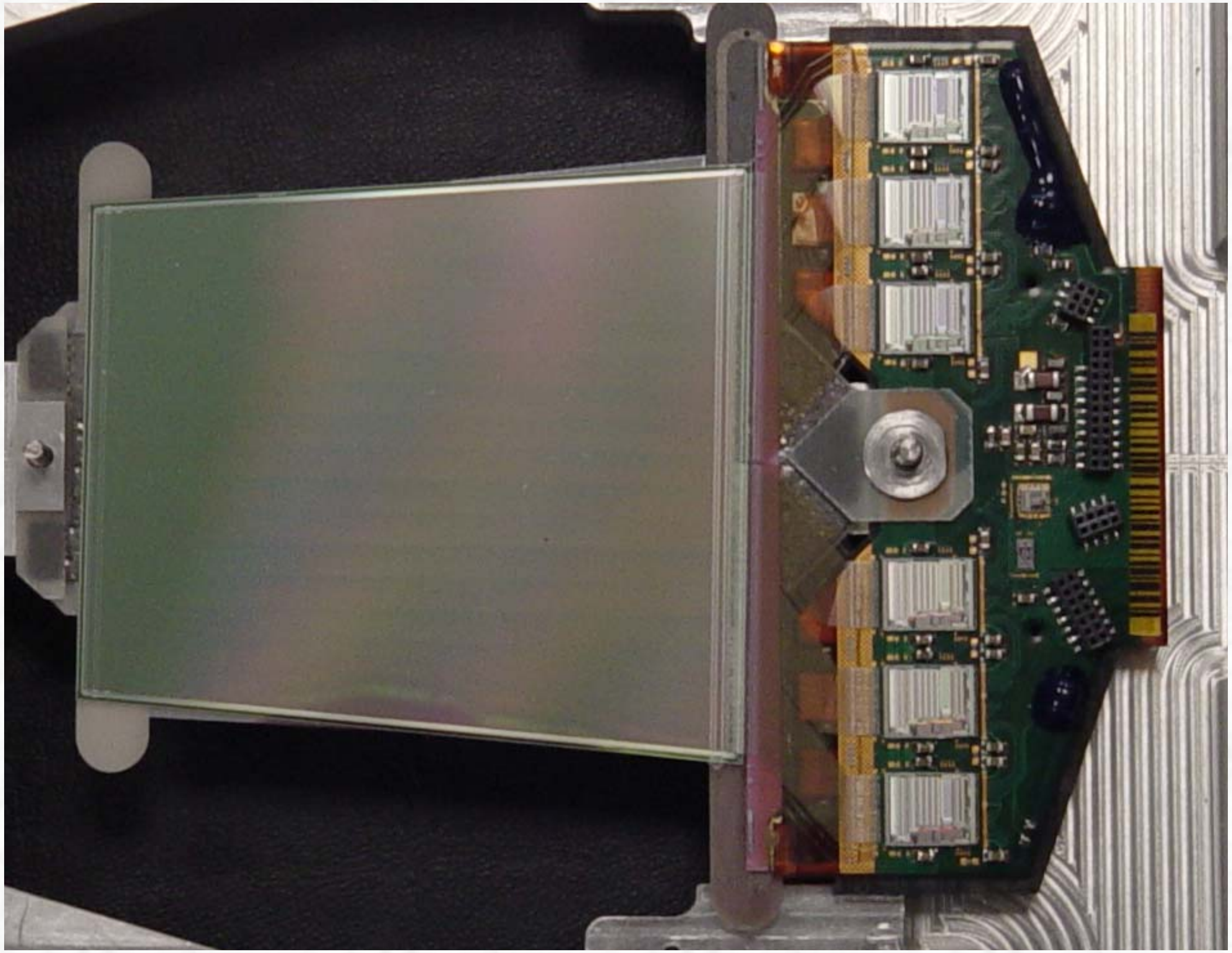
Example: ATLAS SCT Module



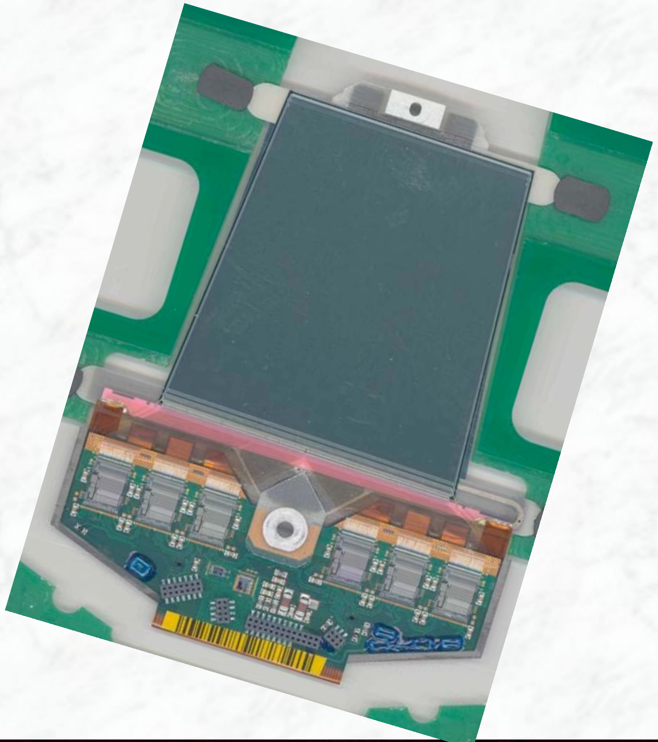
ATLAS Barrel detector

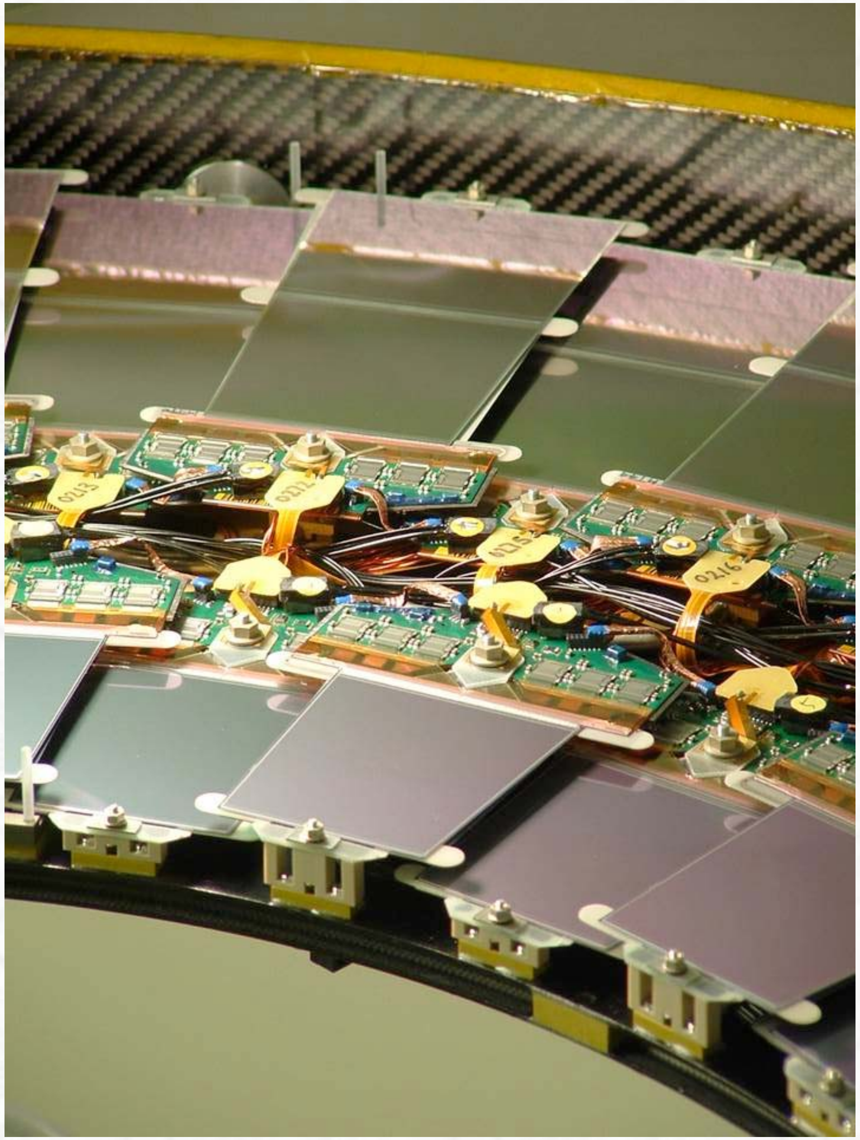


Example: ATLAS Module



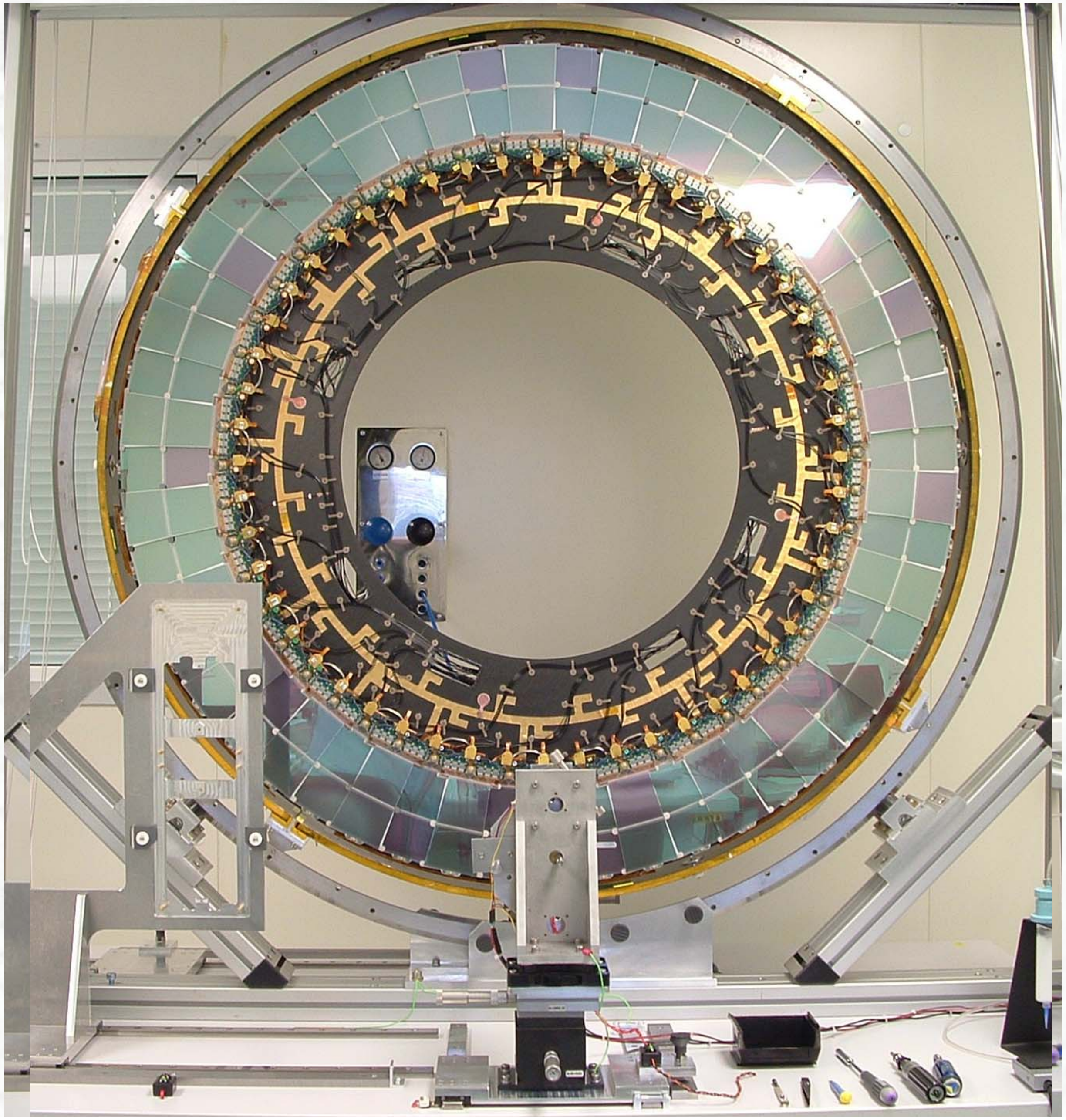
SemiConductor Tracker



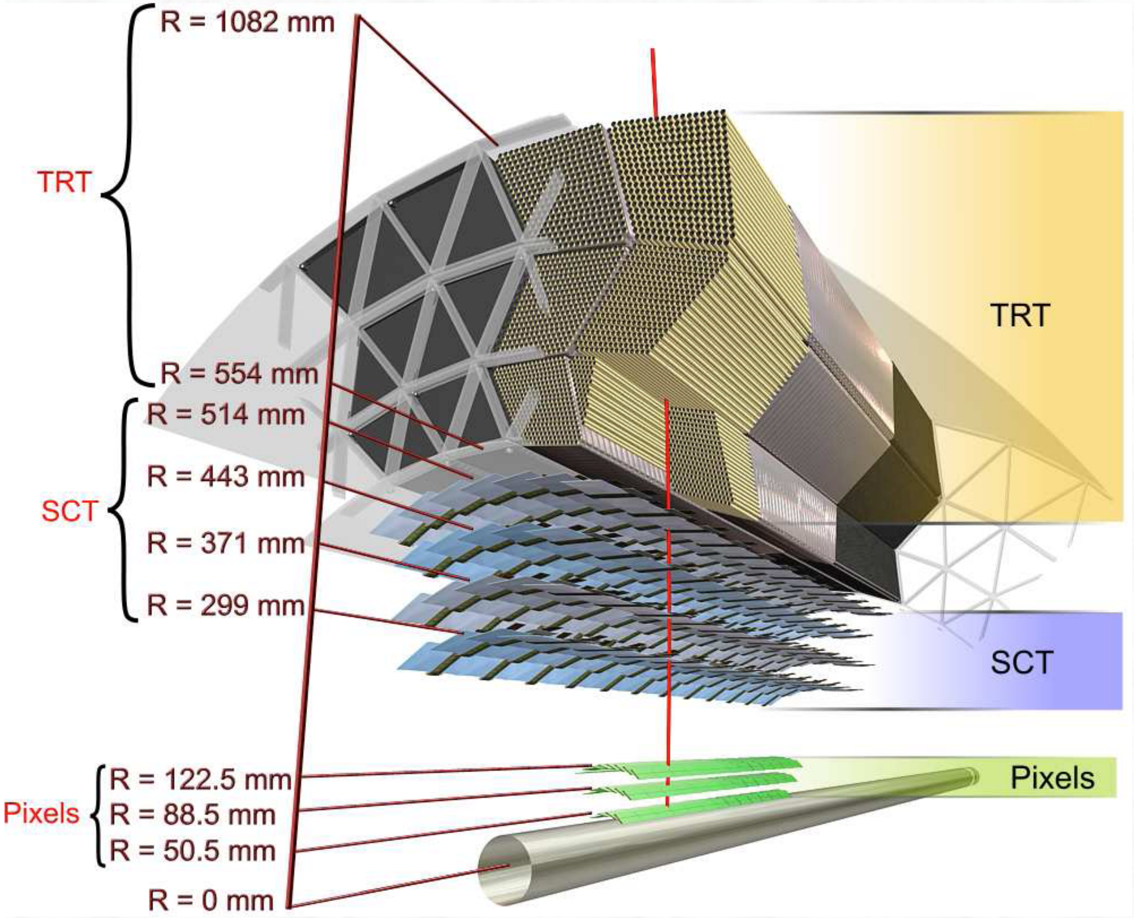


Module fabrication in Freiburg

SCT Endcap



The ATLAS Inner Detector



	R- ϕ accuracy	R or z accuracy	# channels
Pixel	**10 μm**	**115 μm**	**80.4M**
SCT	**17 μm**	**580 μm**	**6.3M**
TRT	**130 μm**		**351k**

$$\sigma/p_T \sim 0.05\%\ p_T \oplus 1\%$$

Layers of the ATLAS detector