The ATLAS Experiment:

Physics Goals and Detector Concept

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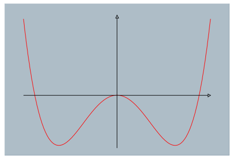
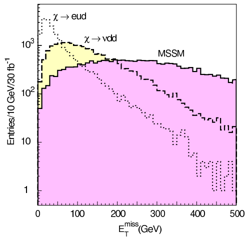
The plan of this lecture

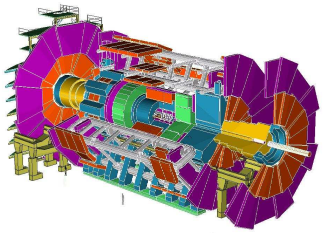
Introduction



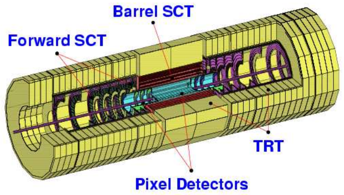
The main physics goal



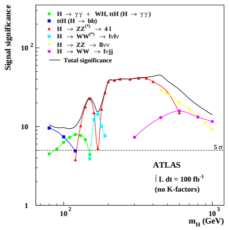
Other physics requirements



The general concept of the ATLAS detector



Some examples of subdetectors



Selected studies of the physics potential

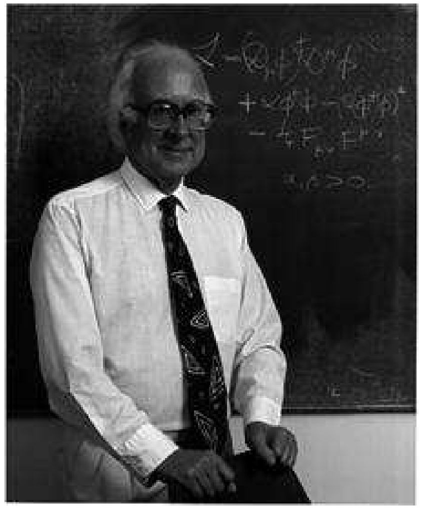
Conclusions and Outlook

A solution - the Higgs boson

The speculation (1965)

- Fundamental particles, fermions as well as bosons, are massless per se.
- Masses are generated by interaction with a background field, the Higgs field. The stronger the Higgs coupling, the larger the particle mass.
- The gauge bosons receive their longitudinal components through spontaneous symmetry breaking.

The father of the thought



Peter Higgs

The consequence

- There has to be a scalar Higgs boson as an excitation of the Higgs field.

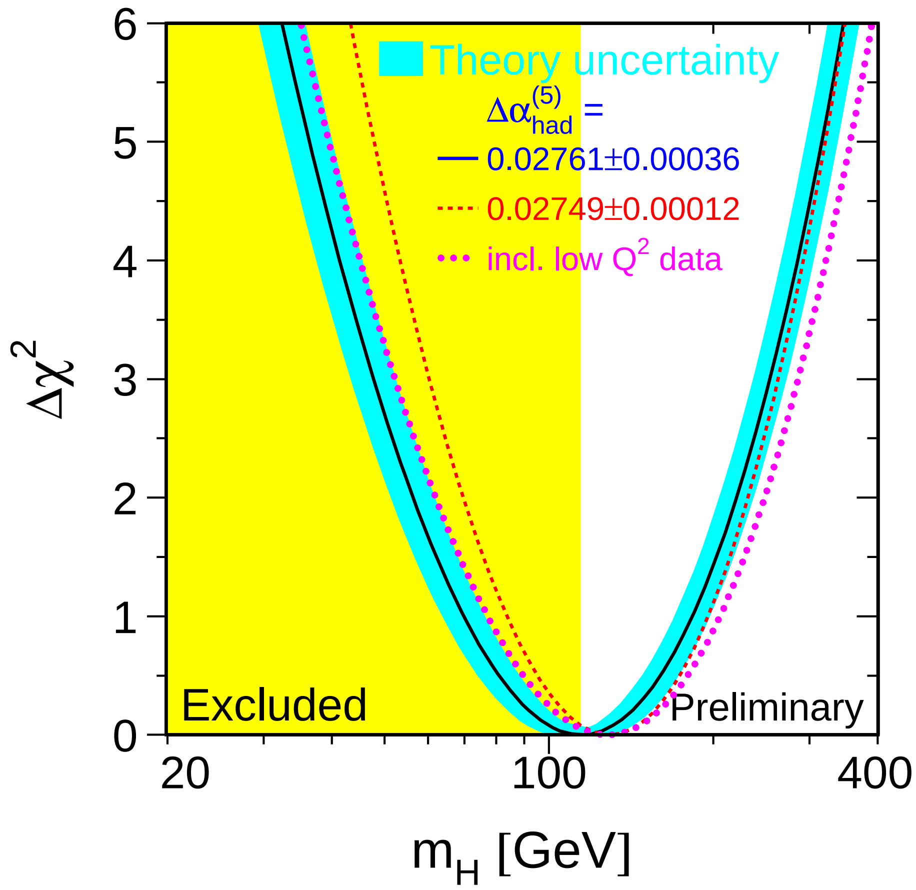
The predictions of the Standard Model

- The couplings of the Higgs boson to all elementary particles are fixed.
- Given a Higgs mass, the decay channels and decay rates of the Higgs boson are fixed.

The Higgs mass is not predicted and has to be measured by experiments.

The Higgs boson within the Standard Model

The Standard Model Fit

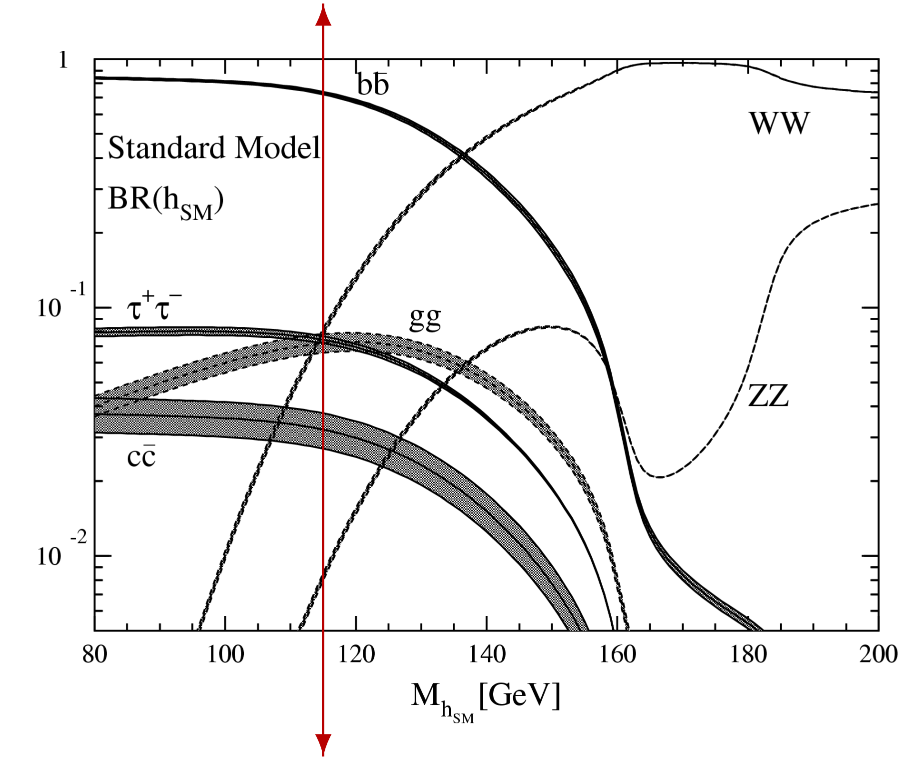


The best value: $M_H = 114^{+69}_{-45}$ **GeV.**

The limit: $M_H < 260$ **GeV with 95% CL.**

The branching ratios

$M_H = 115$ **GeV**

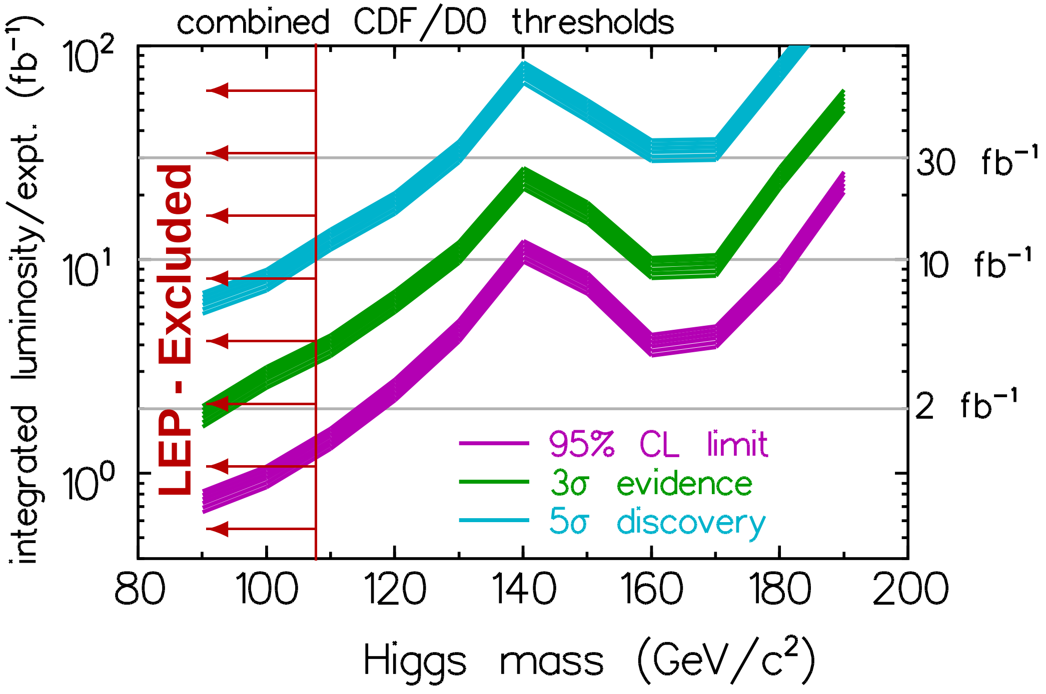


$74\%(H \to b\bar{b})$

$7\%(H \to \tau^+\tau^-, W^+W^-, gg)$

$4\%(H \to c\bar{c})$

Tevatron - the present work horse



Achieved and expected luminosities

$0.05\,\mathrm{fb}^{-1}$ until end of 2002

$0.6\,\mathrm{fb}^{-1}$ until end of 2004

$4-8\,\mathrm{fb}^{-1}$ until end of 2009

Search channels

– $114.1\,\mathrm{GeV} < M_H < 135\,\mathrm{GeV}$, $qq' \rightarrow Z/W \rightarrow Z/WH$.

– $M_H > 135\,\mathrm{GeV}$, $gg \rightarrow H \rightarrow WW^\star$.

A survey: What can be reached within RUN II?

Realist: An improvement compared to LEP is possible if 2 fb^{-1} of luminosity is collected.

Pessimist: With 10 fb^{-1}, masses up to $M_H = 180\,\mathrm{GeV}$ can be excluded with 95% CL.

Optimist: For $M_H = 116\,\mathrm{GeV}$ and 15 fb^{-1} a five sigma discovery is possible.

Everything is possible, we have to wait, and in order to be sure, build...

The LHC - a proton-proton accelerator (2007^{++})

Alice

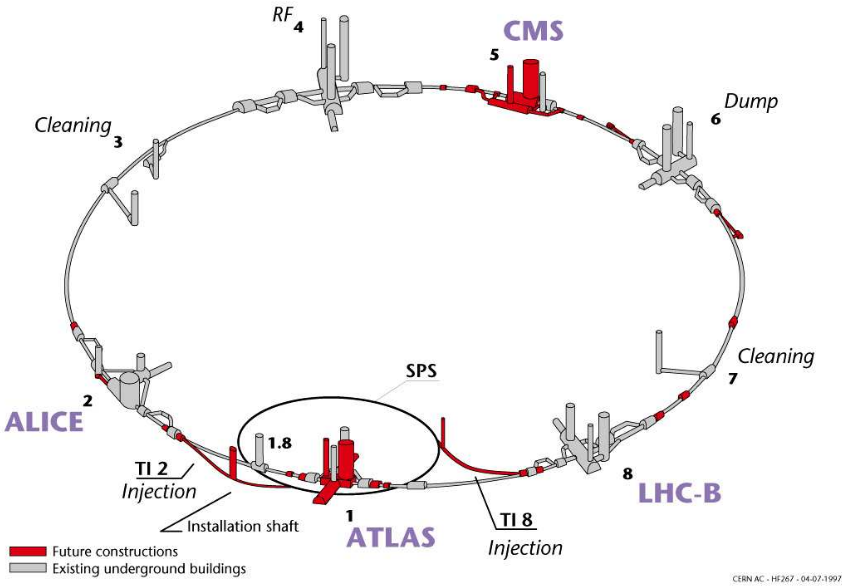
Heavy Ions, ...

LHC-B

Matter $\leftrightarrow$ Antimatter, ...

ATLAS / CMS

Higgs production, ...



Technical details

L = 26.7 km
E_p = 7 TeV
$N_p = 1.1 \cdot 10^{11}$ / beam
$t_{BC} = 25$ ns
$N_{ev} = 25/BC$

Lumi expectations

10 fb^{-1} / y at start
100 fb^{-1} / y nominal

The Heart of the LHC - the superconducting magnets

length	15 m
weight	23.8 t
B-field	8.3 T
temperature	1.9 K
current	12000 A
energy	7.1 MJ

LHC - the revised schedule

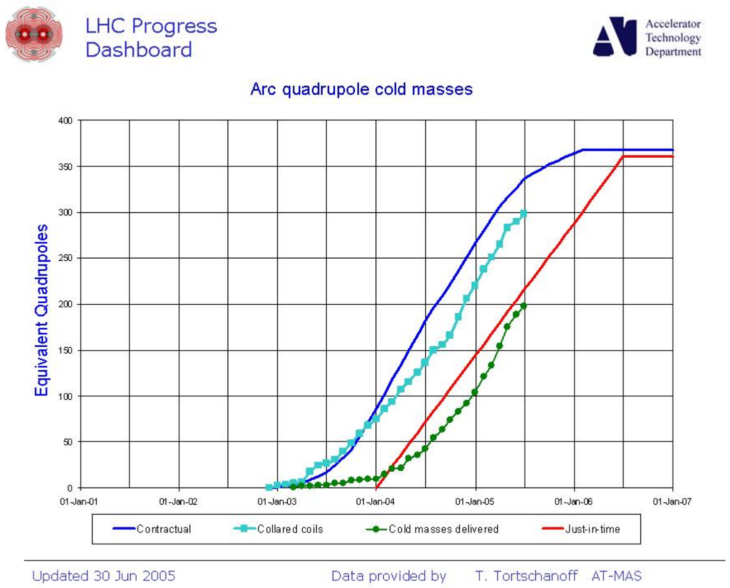
Dec. 2006: The ring is closed and cold.

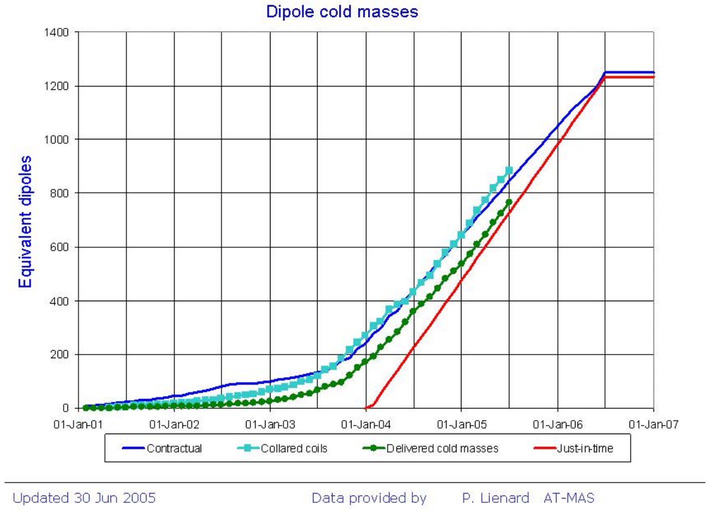
Jan.-Mar. 2007: Time for machine commisioning.

Spring 2007: First collisions and pilot run with $\mathcal{L} = 5 - 20 \cdot 10^{32}$/cm^{2}s and $\mathcal{L}_{\mathrm{int}} < 1\,\mathrm{fb}^{-1}$. Start the detector commisioning with $\mathcal{O}(10^5)$ events each for the $Z \rightarrow \ell^+\ell^-$, $W \rightarrow \ell\nu$ and $\mathrm{t\bar{t}}$ final states.

Jun.-Dec. 2007: Complete detector commisioning and start the first physics run.

2009^{++}: Achieve $\mathcal{L} = 1 - 2 \cdot 10^{34}$/cm^{2}s and $\mathcal{L}_{\mathrm{int}} = 100\,\mathrm{fb}^{-1}$/y, which means high luminosity LHC running.





Hurry up, it may only be 1 year, 10 month, 13 days, 9 hours and 20 minutes to LHC physics.

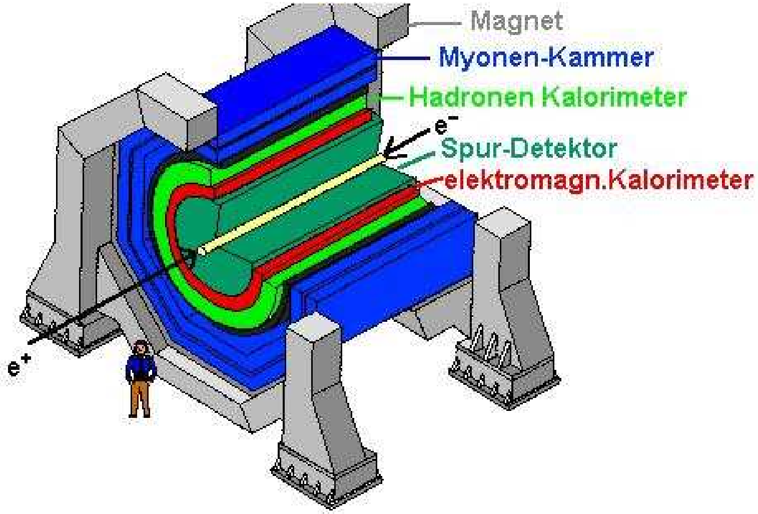
Detector requirements from the various processes

- **SM Higgs:** Needs high resolution e, μ and γ detection, and excellent secondary vertex detection for τ-leptons and b-quarks. In addition Higgs searches aim for a stand-alone muon-system at high energies and forward jet production for the VBF channel.
- **SUSY:** The main signature of SUSY channels is E_T^{miss}. This needs hermeticity.
- **New heavy bosons (Z', ...):** The boson decays will result in high-p_{t} leptons, which need charge determination up to p_{t} of several TeV, which means large bending power.
- **Compositeness:** Will produce high-p_{t} jets which needs good hadron calorimetry.
- **W- and Top-mass:** The yield is $8 \cdot 10^6 \mathrm{t\bar{t}}$ and $3 \cdot 10^6 W$ for $\mathcal{L}_{\mathrm{int}} = 10\ \mathrm{fb}^{-1}$, $\Rightarrow \sigma(M_{\mathrm{top}}) = 2\ \mathrm{GeV}$, $\sigma_{\mathrm{stat}}(M_{\mathrm{W}}) = 2\ \mathrm{MeV}$. The precise mass determination needs good knowledge of the absolute energy scale of the calorimeters.
- **CP-Violation and B-decays:** The yield is $10^{12} \mathrm{b\bar{b}}$ for $\mathcal{L}_{\mathrm{int}} = 10\ \mathrm{fb}^{-1}$. Needs excellent secondary vertex detection, and full reconstruction of final states with low-p_{t} particles.

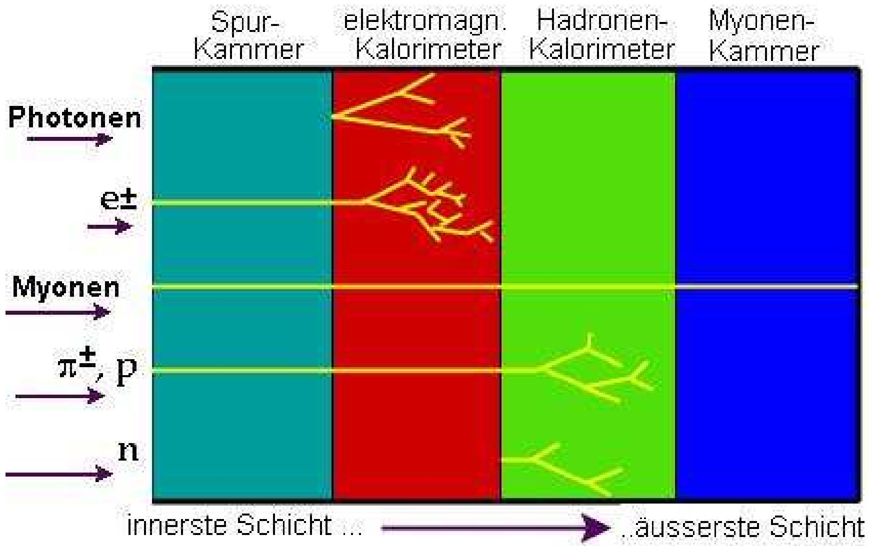
The various channels represent strong challenges for the detector performance.

The general layout of particle detectors

With the onion-skin-principle...



...we get them (almost) all



$\vec{x}, \vec{v}, \vec{p}$ $\vec{x}, E$ $\vec{x}, E$ $\vec{x}, \vec{p}$

Some basic decisions to be made

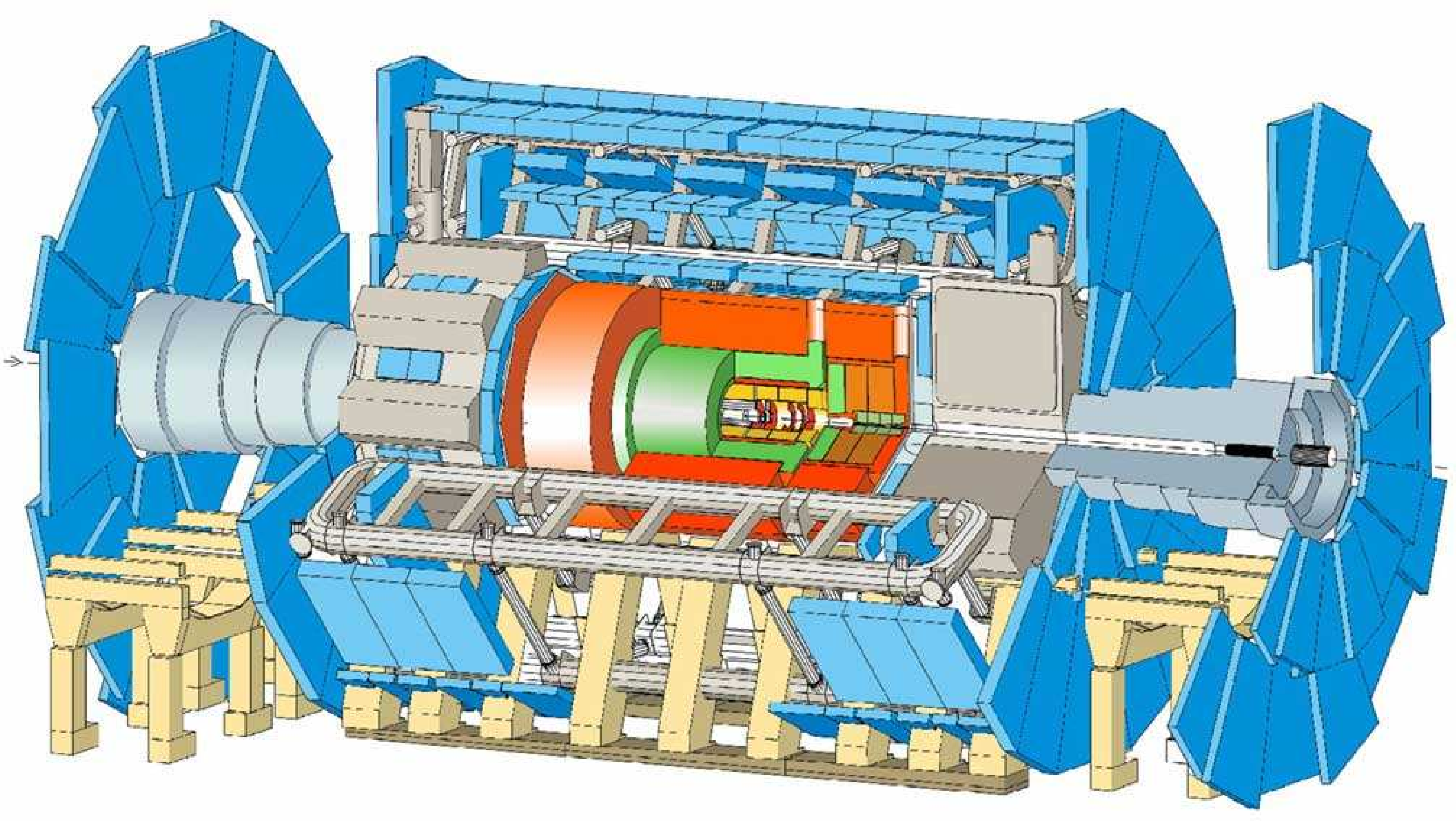
— **Where to put the coil for the central magnetic field.**

— **How to minimise the dead material in front of the electromagnetic calorimeter and also between the electromagnetic and hadronic sections of the calorimeter.**

— **How to minimise the multiple scattering in the muon system.**

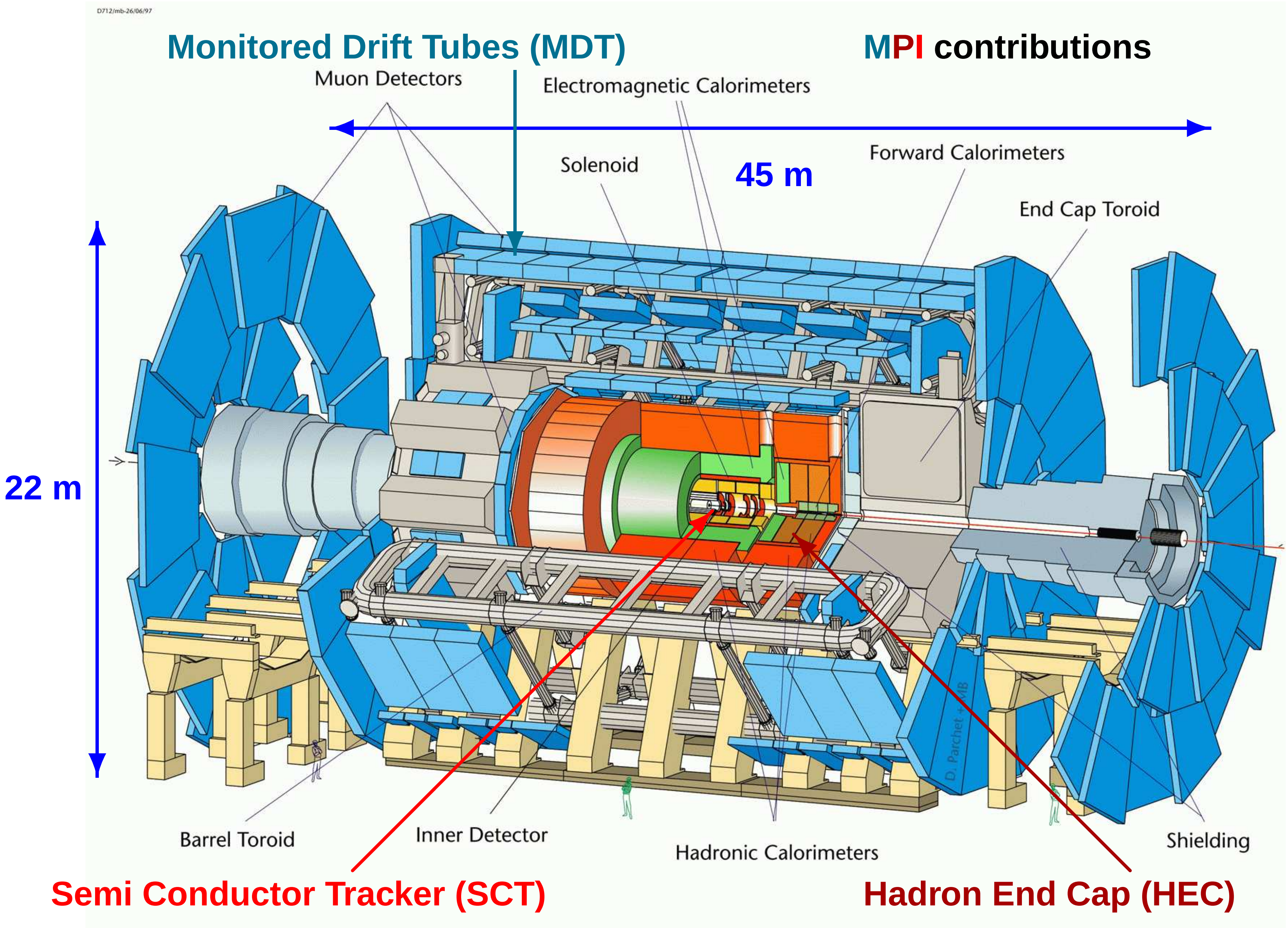
The answers to these questions result in different detectors.

The ATLAS detector - general layout

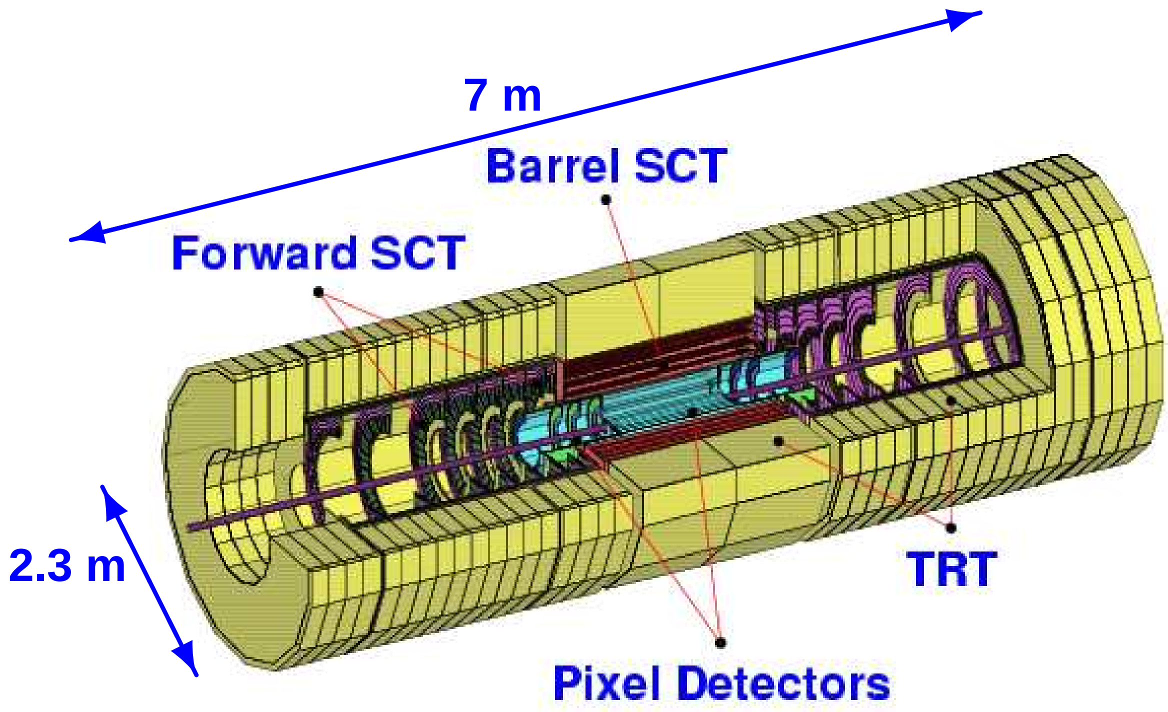


– Silicon tracker
– Transition radiation tracker (Xe)
– Central solenoid ($B = 2$ T)
– Electromagnetic calorimeter (Pb, LAr, 25 X_0)
– Hadronic tile calorimeter (Fe, Szi, 11 λ)
– Hadronic end cap (Cu, LAr, 11 λ)
– Forward calorimeter (Cu/W, LAr, 11 λ)
– Air toroid magnet ($B = 4$ T)
– Muon spectrometer (MDT/CSC, RPC/TGC)

MPI contributions to the ATLAS detector



The ATLAS inner detector



At MPI we have built 424 modules of the middle type for the SCT forward detector.

The Pixel Detector

- Radius 4.8 — 16 cm.
- 3 layers, 10 disks.
- $1.4 \cdot 10^8$ read-out channels.
- σ: $12\ \mu m$ ($R\Phi$) and $\approx 70\ \mu m$ (z/R).

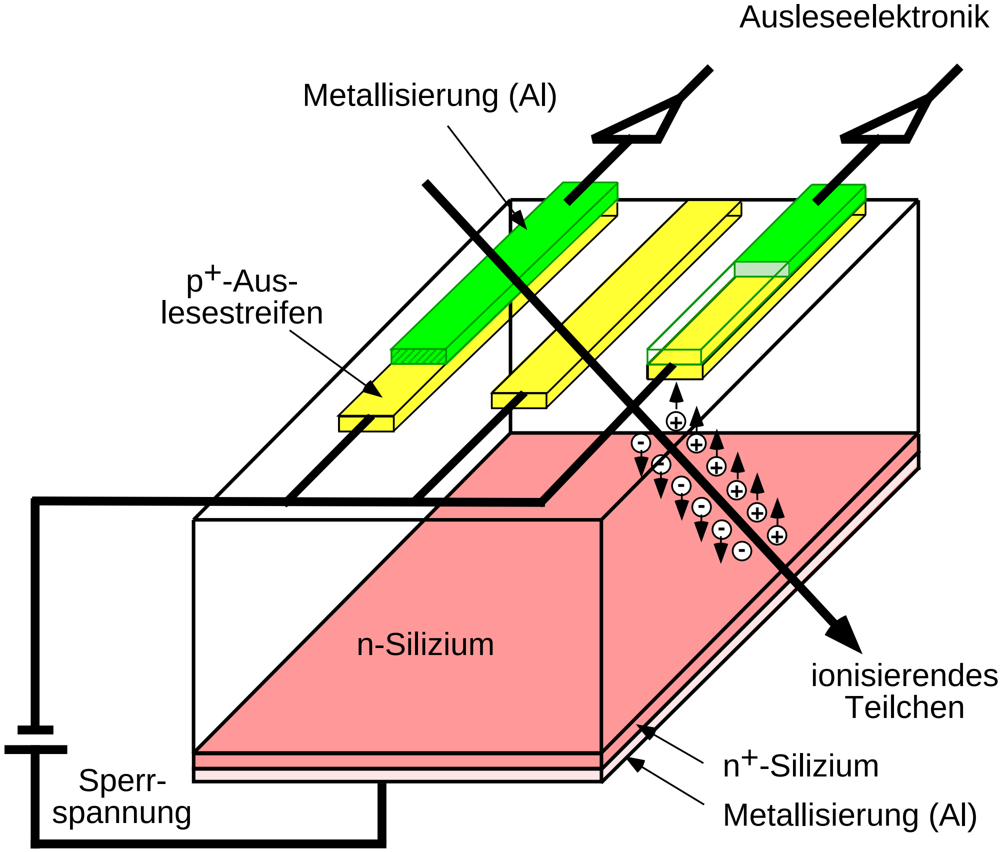
The Semi Conductor Tracker

- Radius 27 — 52 cm.
- 4 layers, 18 disks
- $6.3 \cdot 10^6$ read-out channels.
- 4088 modules, 61 m^2 silicon
- σ: $16\ \mu m$ ($R\Phi$) and $580\ \mu m$ (z/R).

The Transition Radiation Tracker

- Radius 56 — 107 cm.
- 100 k / 320 k straws in barrel / endcap.
- 420 k read-out channels.
- Xe radiator for electron-detection.
- σ: $170\ \mu m$ / per straw.

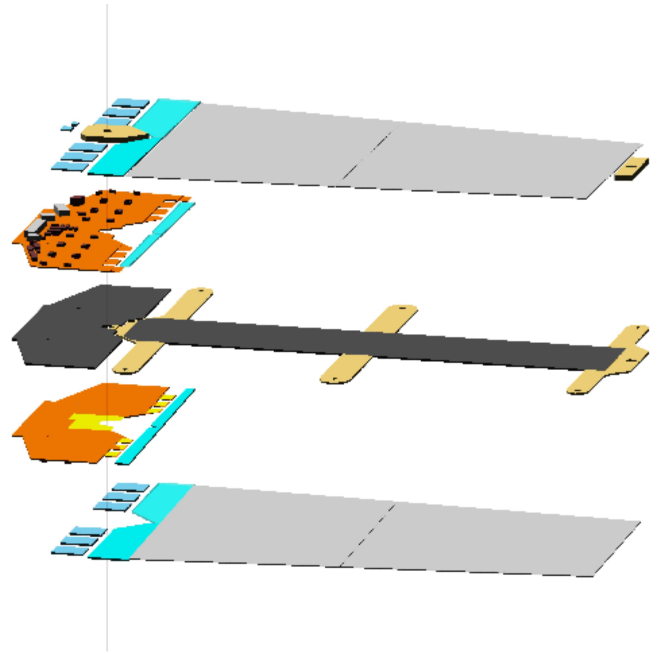
SCT modules - general layout and performance

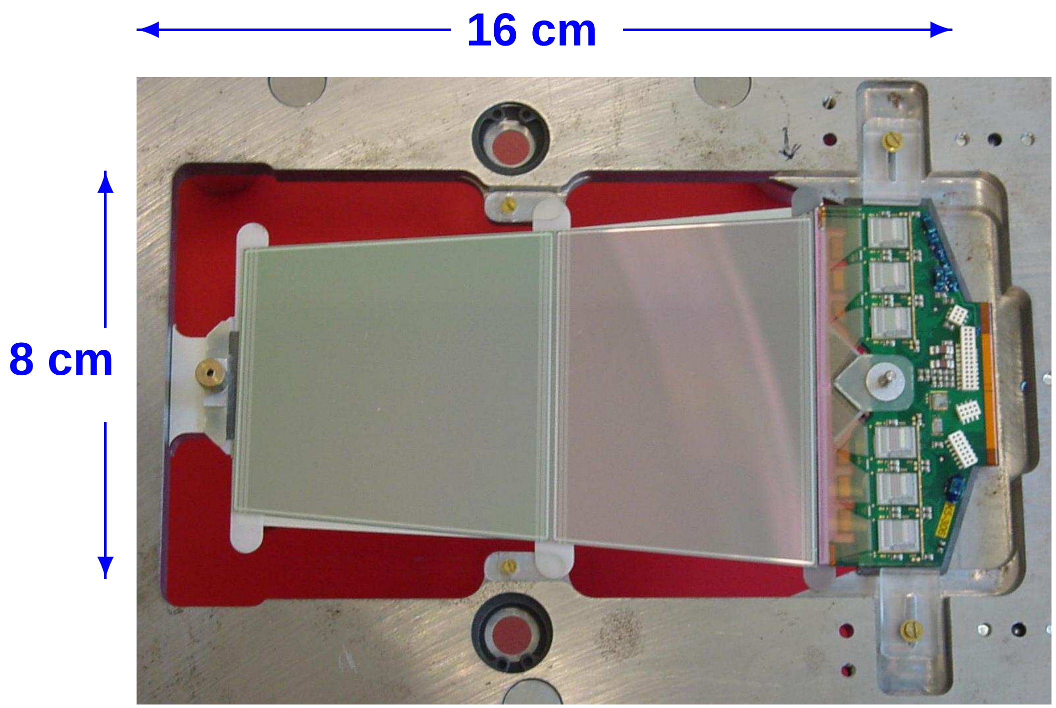


- Rapidity coverage: $|\eta| < 2.5$.
- Radiation dose: $2.6 \cdot 10^{14}$ p/cm^2 in 10 y LHC.
- $\sigma = 16(580)\ \mu m \perp (\|)$ to the strips.
- Two-track resolution: $200\ \mu m$.
- Strip length: 12.8 cm.
- Bias voltage: < 500 V.
- Produced heat: 7 W per forward module.
- Gain: 50 mV/fC.
- Signal charge: 3.3 fC, $S/N = 10$.
- Noise occupancy: $< 5 \cdot 10^{-4}$.
- Hit efficiency: $> 99\%$.

The SCT will be used as vertex and precision tracking detector.

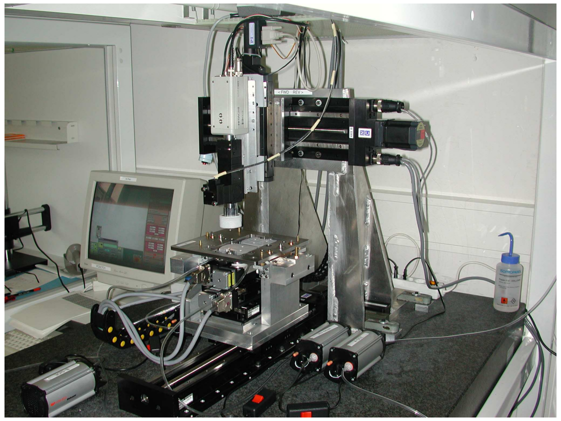
From the model to a module is a long way

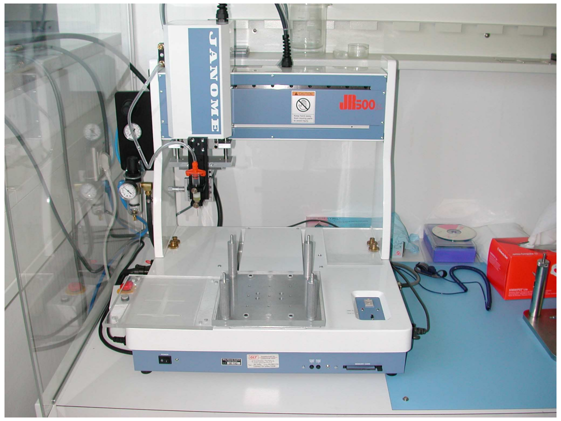




The most important things are

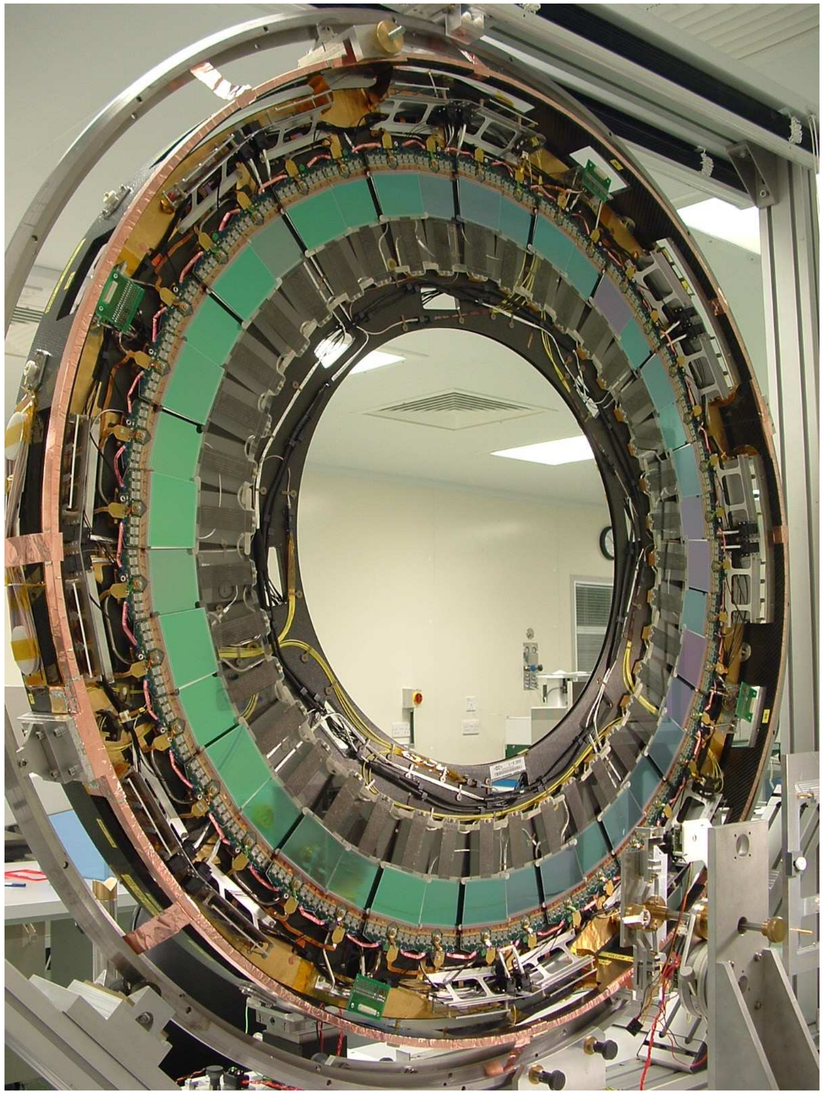
- A robot to align the silcon detectors with a precision of better than 5 μm.
- A glue-robot to control the thickness of the module.
- A lot of patience. The rate of module production is 2 modules per day.



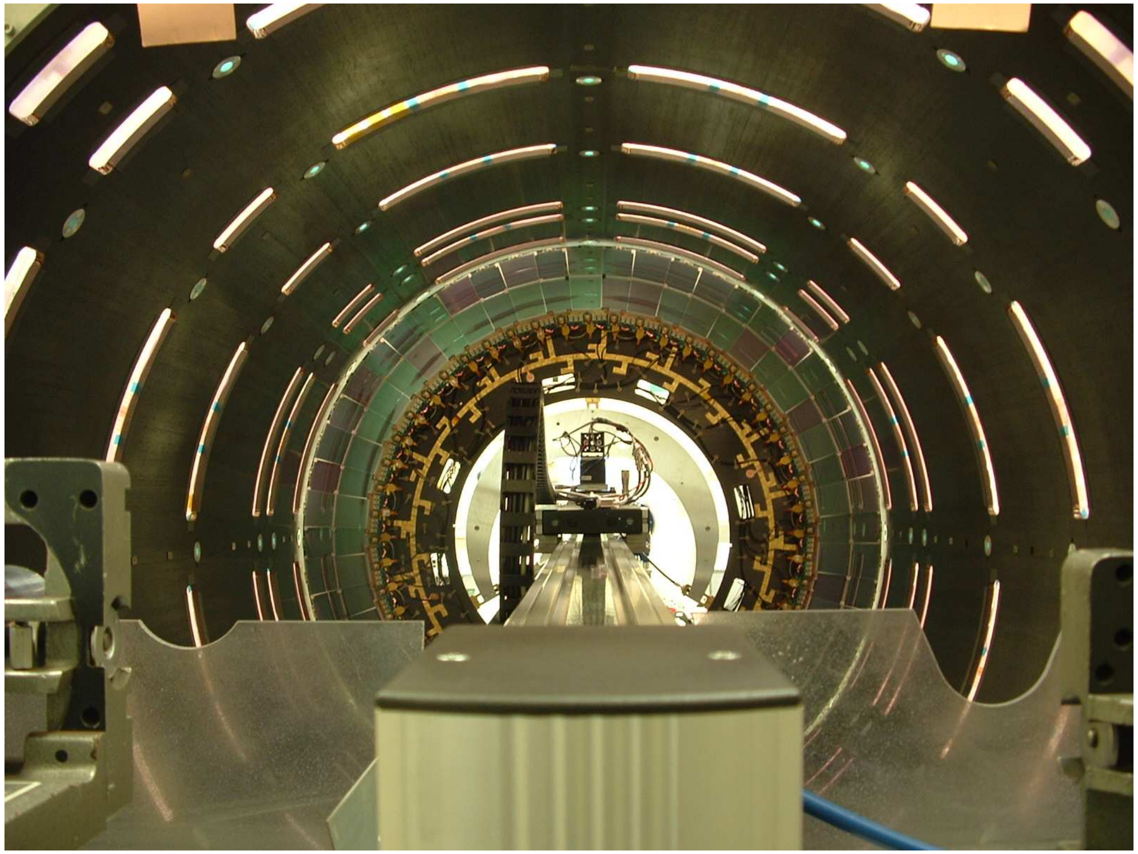


The first disc installed in the cylinder at Liverpool

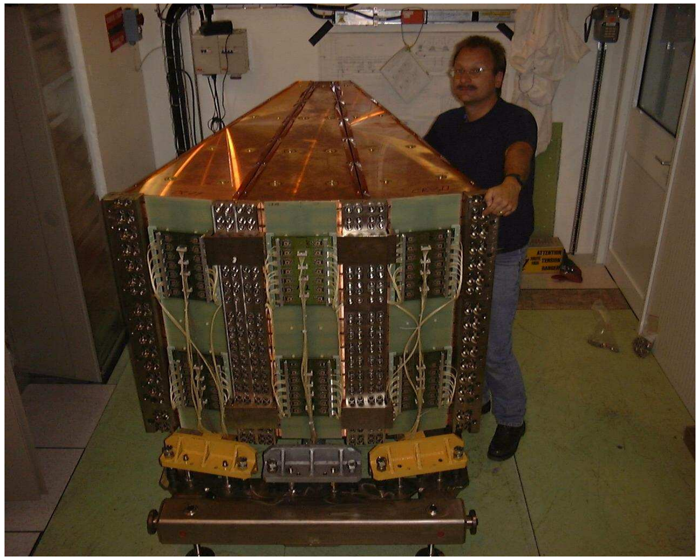
First of 8 discs with MPI modules

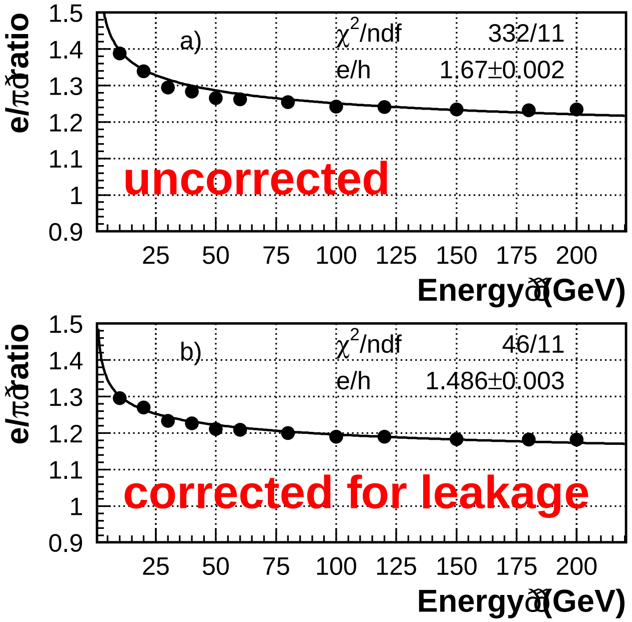


The first disc in a the cylinder of Endcap C



The ATLAS HEC - a hadron calorimeter





General considerations

- Hadron showers, π, contain a purely hadronic, h, and an electromagnetic, e, part with fraction f. The e part stemms from $\pi^0 \to 2\gamma$, $\Rightarrow$ $\pi = h\,(1-f) + e\,f$.
- For the hadronic part about 20% of the energy remains invisible (i.e. nuclear resonances). Therefore, hadronic showers have larger fluctuations than electromagnetic.
- From measuring e and π one gets the intrinsic e/h ratio.

The ATLAS Hadronic End Cap

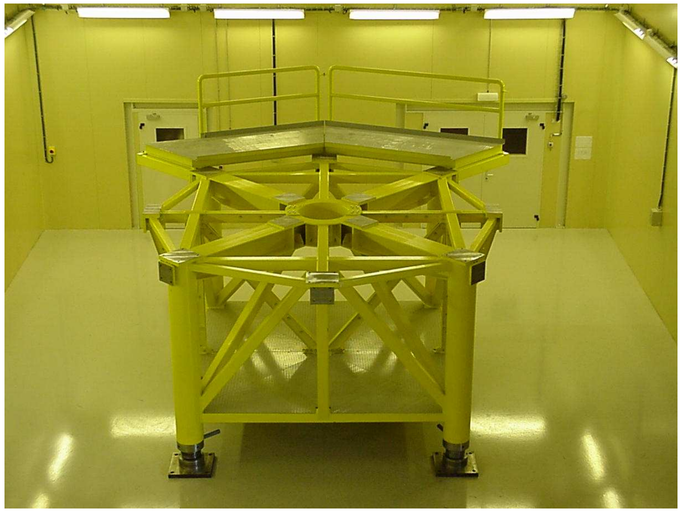
- The sensitive material is liquid Argon, LAr.
- The absorber is made of 25 mm thick Cu-plates, with a total thickness of about 11λ.
- The measured resolution for hadronic showers is:

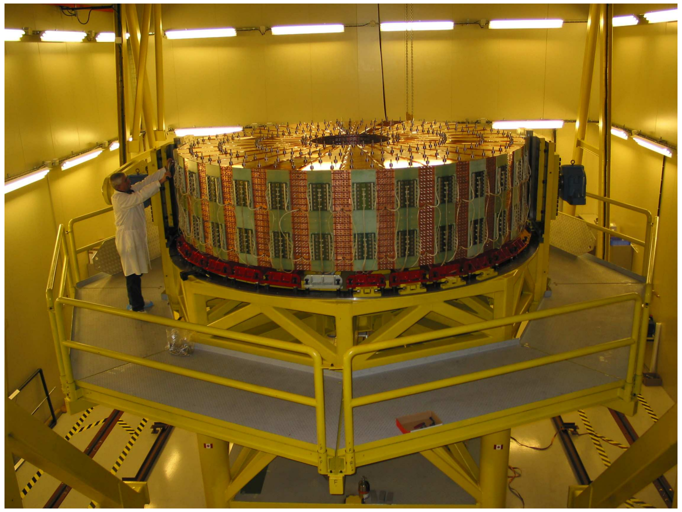
$$\frac{\sigma(E_e/E_\pi)}{E} = \frac{22/70\,\%}{\sqrt{E/GeV}} \oplus 0.3/6\,\%.$$

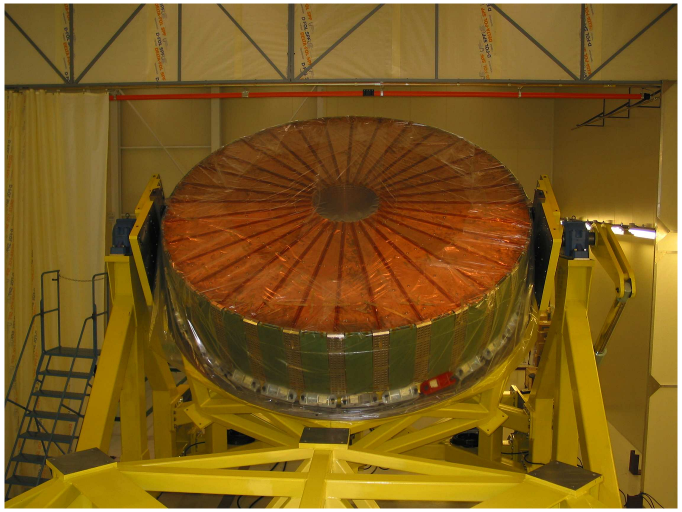
At MPI we have build 27 HEC modules.

HEC - general layout and wheel construction

– The HEC consists of four wheels, two at each end, and covers the range $1.5 < |\eta| < 3.2$.
– A wheel contains 32 modules, has a radius of 2.1 m and a weight of 67 tons.
– A module has 4 longitudinal segments and a granularity in $\Delta\eta \times \Delta\phi$ of 0.1×0.1, (0.2×0.2) for $1.5 < |\eta| < 2.5$, ($2.5 < |\eta| < 3.2$).

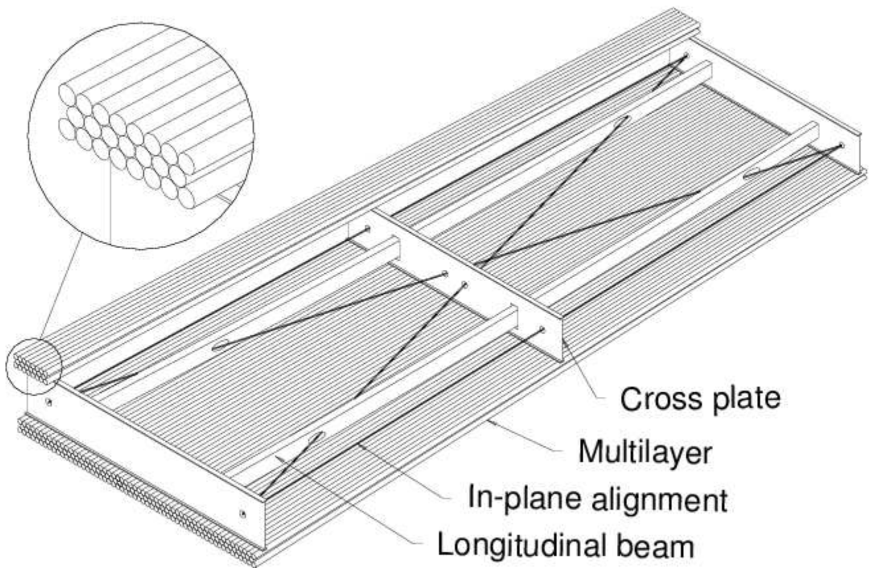






Putting a wheel together is a delicate job.

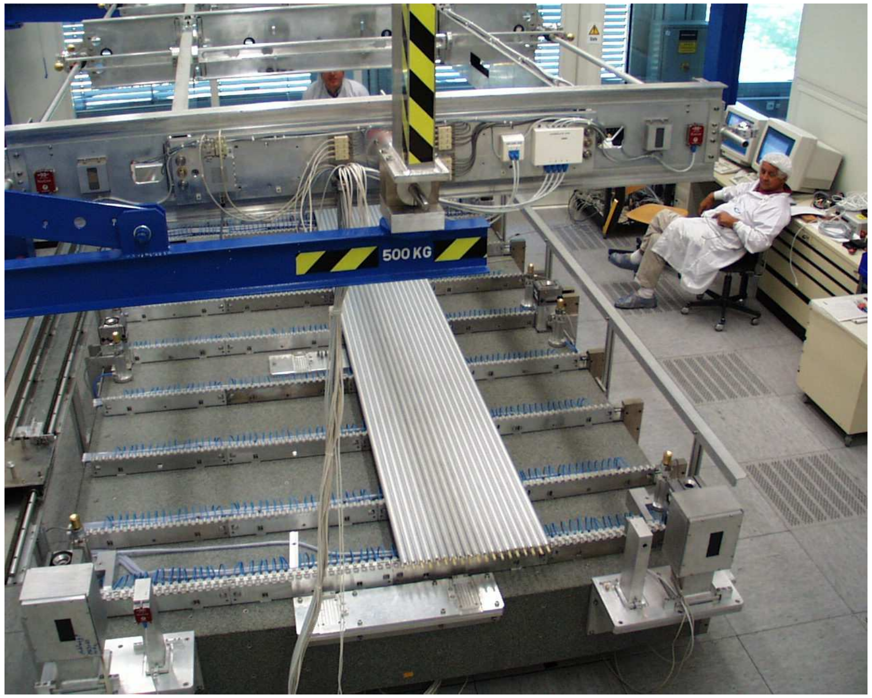
MDT chambers - general layout and performance



— Each chamber has two times three (four) layers of Al tubes of 30 mm diameter and 400 μm wall thickness with a central, gold-plated W/Re (97/3) wire of 50 μm thickness.
— The gas is Ar/CO_2 (93/7$\%$) at 3 bar pressure.
— The gas-gain is $2 \cdot 10^4$ at 3080 V potential.
— The maximum drift time is 700 ns with a drift velocity of about 30 μm/ns.
— The single wire resolution is 100 μm and the chamber resolution is 50 μm.
— The chambers are oriented in projective towers with three layers each. In the barrel the layers are located at $R = 5, 7.5$ and 10 m.
— Within towers, the alignment will be optically monitored during operation to within 30 μm.
— The tower-to-tower alignment, done only at installation time, aims for $\mathcal{O}$(1 mm) precision.
— The p_{t} resolution for muons is better than 10$\%$ up to 1 TeV and the invariant mass resolution e.g. for $H \rightarrow ZZ^{\star} \rightarrow 4\mu$ ranges from 2-2.4$\%$ for M_H ranging from 130-200 GeV.

At large luminosities, the muon system can be used stand-alone to discover heavy Higgses.

Construction of an MDT chamber



Many things have to be done

- Mount 432 tubes of 3.8 m length, with a precision of 20 μm (thickness of a hair).
- Mount 1728 (tight!) gas connection.
- The weight of a chamber is about 350 kg.

Very precise tools are needed to properly do the job.

Mass production of chambers

There are very many chambers

- For ATLAS one needs 1200 MDT chambers produced at 13 institutes.
- At MPI 88 chambers are being build.
- This means 38016 tubes and 152064 gas-tight connections.

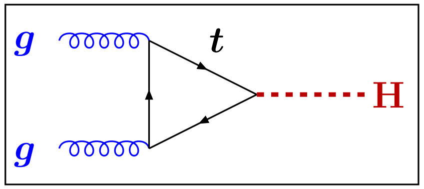
A complex logistics is needed

- The chambers are being tested with cosmic muons.
- They are stored for several years.
- The transport has to be secure.

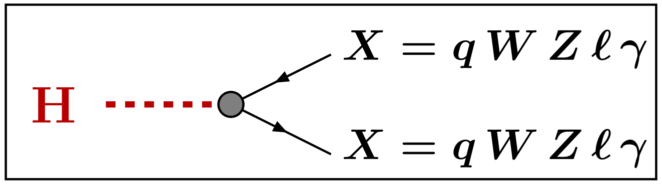
The production time is about 6 years.

Search for the Higgs boson at the LHC

— The dominant channels for

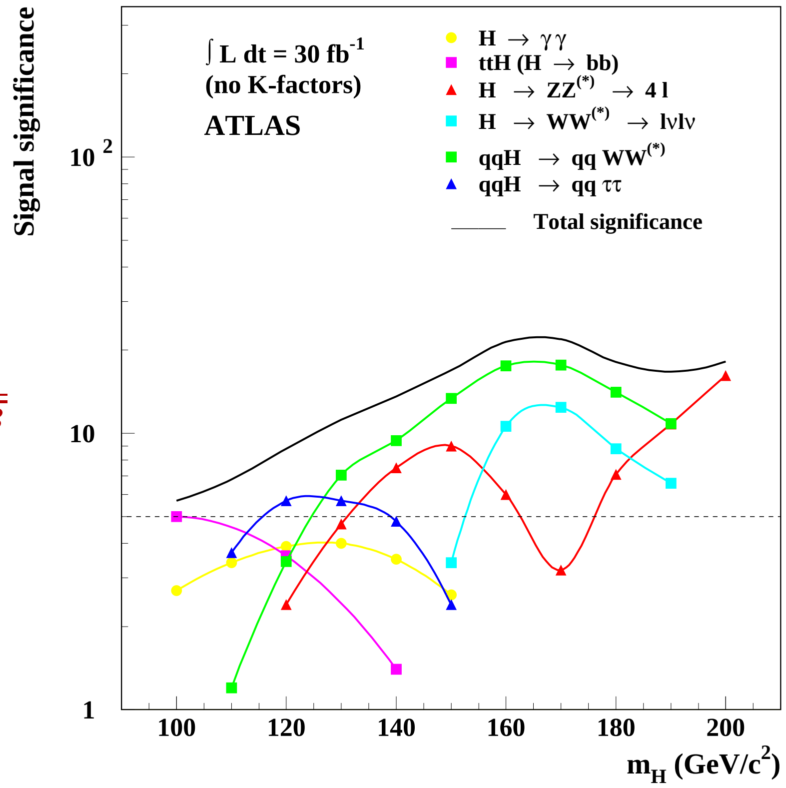


production and

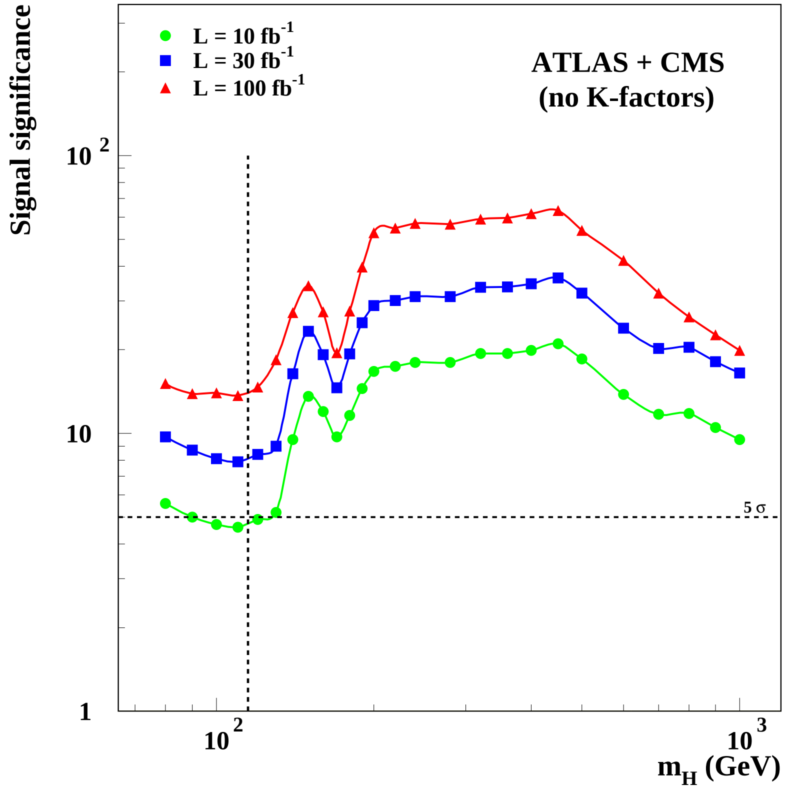


decay.

$\frac{S}{\sqrt{B}}$



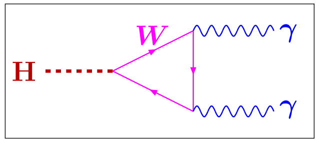
$\frac{S}{\sqrt{B}}$

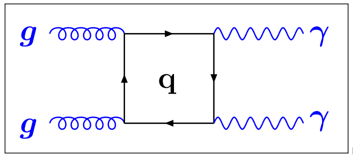
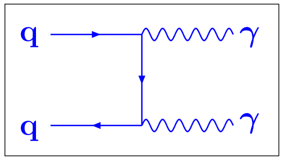
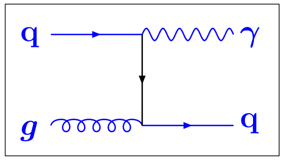


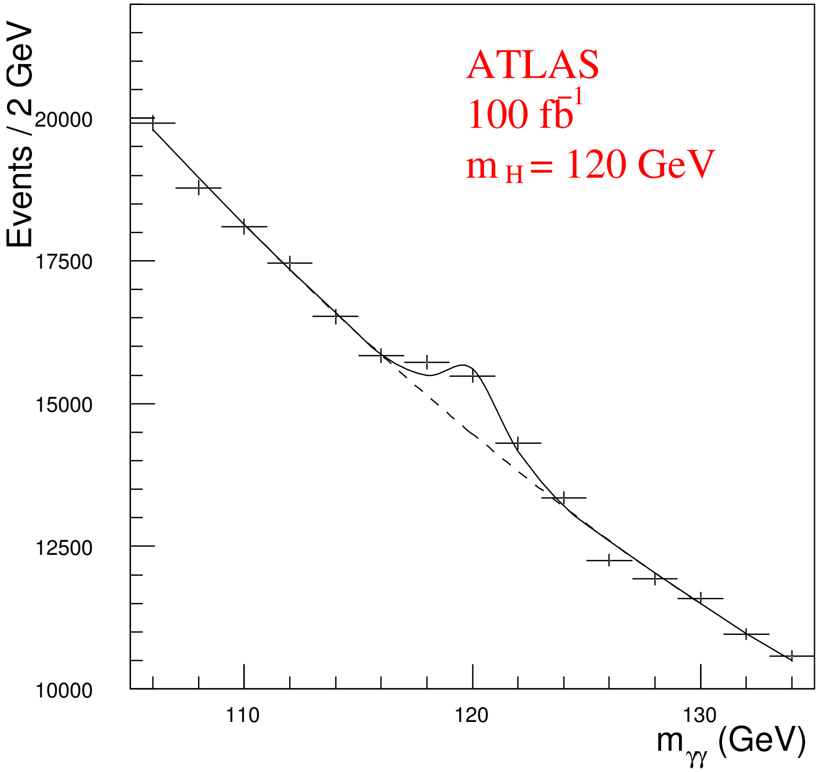
For the favourite mass region $H \longrightarrow b\bar{b}$, $H \longrightarrow \gamma\gamma$ and $H \longrightarrow WW^{\star}$ are important.

For the whole mass region, the combined sensitivity is better than 5σ.

An example - the channel $H \to \gamma\gamma$

— In the mass region $80\ \mathrm{GeV} < M_H < 150\ \mathrm{GeV}$  is an important channel.

— Background: ,  and  with $q \to \pi^0 \to 2\gamma$.



The perspectives

— The rate is small, but the events are very clean.

— The analysis requires an extremely precise electromagnetic calorimeter to separate single γ's from $\pi^0 \to 2\gamma$. The required π^0 rejection is 10^7.

— With one year of nominal luminosity one can achieve a 4σ discovery.

A promising channel for light Higgs bosons which needs an excellent electromagnetic calorimeter.

Conclusions and...

— The main physics goal at the LHC is the study of electroweak symmetry breaking, i.e. the discovery of the Higgs boson.

— Together with other topics like SUSY, searches for new heavy bosons or compositeness, precision measurements of the W- and top-mass, study of CP-Violation and B-decays, the short time between bunch-crossings and the high event rate, this constitutes strong challenges for the detector design and performance.

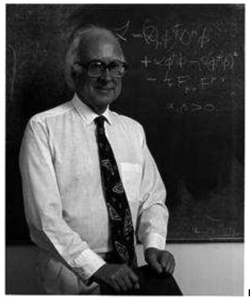
— At ATLAS the choice has been made for a large air toroid magnet to achieve a stand-alone muon system at large luminosities.

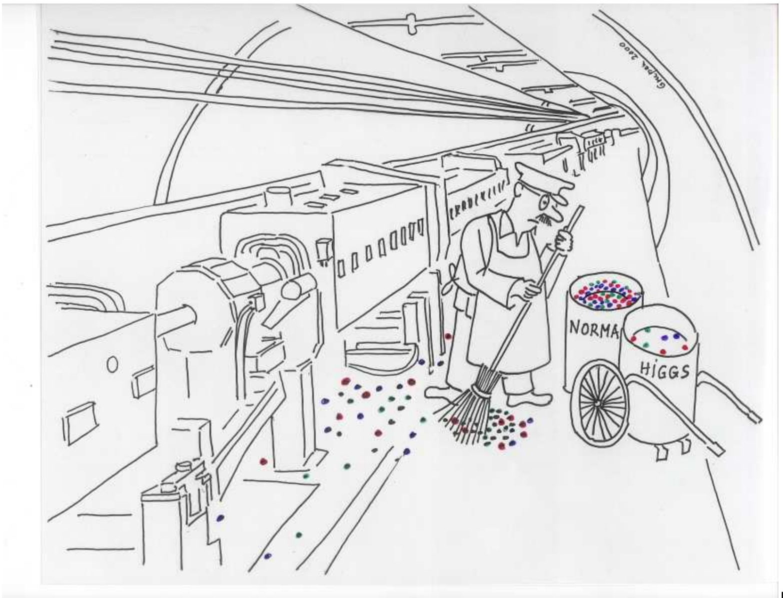
— The MPI makes a large contribution to the construction of ATLAS within the MDT, HEC and SCT groups.

— Studies within the ATLAS TDRs, and test beam measurements of several components, give confidence that the goals can be reached.

What ever happens, it is very likely that within 3-6 years we know which mechanism is responsible for the generation of particle-masses.

...Outlook

It started with , ...

...continued like 

, and will end...

...  in:

H^0 § $J^{PC} = 0^{++}$

Charge = 0
Mass m = 120.3 ± 0.1 GeV [a]
Full width $\Gamma = 2.20 \pm 0.18$ MeV [b]

H^0 DECAY MODES	FRACTION	CL
$b\bar{b}$	$(66.3 \pm 1.9)\%$	95%
WW	$(13.5 \pm 3.4)\%$	95%
$\gamma\gamma$	$(0.21 \pm 0.09)\%$	95%

§ Particle Data Group,
Eur. Phys. J. Cyy, 20xx.