

Experimenteller Nachweis des Higgs Teilchens

Lehrerfortbildung Zeuthen, 25. November 2013
Christoph Rembser (CERN)

Wichtiger Hinweis

- Die Detektoren und Beschleuniger für die Experimente der Teilchenphysik sind sehr komplex und kommen aus Anwendungen von Erkenntnissen aus vielen Gebieten der Physik wie Mechanik, Elektronik, Materialwissenschaften, Teilchenphysik.
- Um einen Teilchenphysikdetektor zu verstehen, ist es am besten einmal selber mit Detektoren gearbeitet zu haben.
- Hier daher nur ein kleiner Überblick...
- ...der auch nicht unbedingt objektiv ist - eigene Erfahrungen (und Vorlieben) fließen natürlich ein!
- Bei weiteren Fragen wenden Sie sich bitte an Ihren Physiker oder Professor an der nächsten Universität.

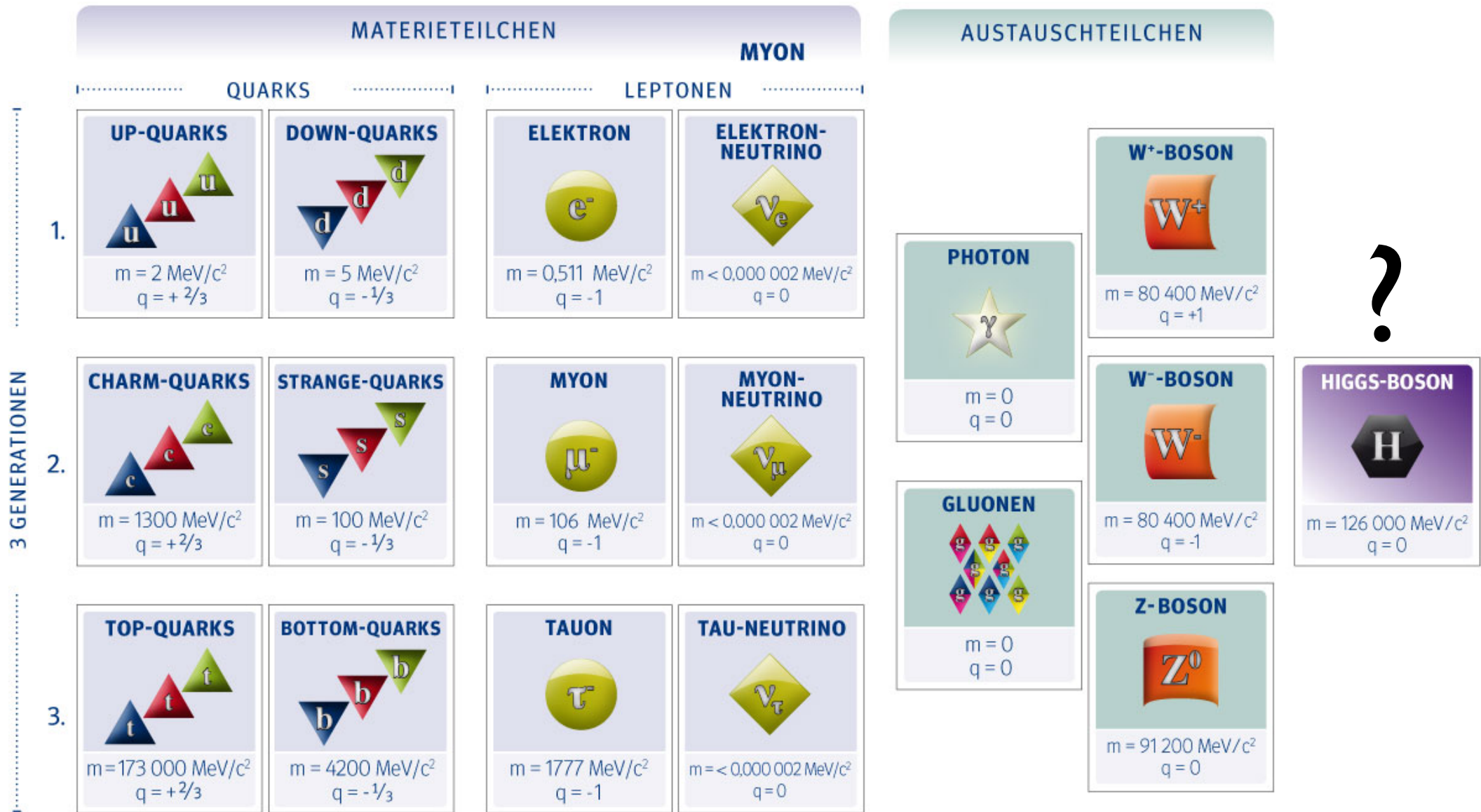
Wofür sind Beschleuniger und Detektoren gut?

- Ziel: Verständnis der Regeln der Natur!
Dafür machen die Teilchenphysiker “Schnappschüsse vom frühen Universum” - Teilchendetektoren sind also Kameras;
➡ ...genauso wie man aus Photos Fußballregeln lernen kann.



➡ LHC: Photos vom Universum $\sim 10^{-10}$ s nach dem Big Bang

Das Standardmodell der Teilchenphysik



?

Gesucht: das Higgs Boson

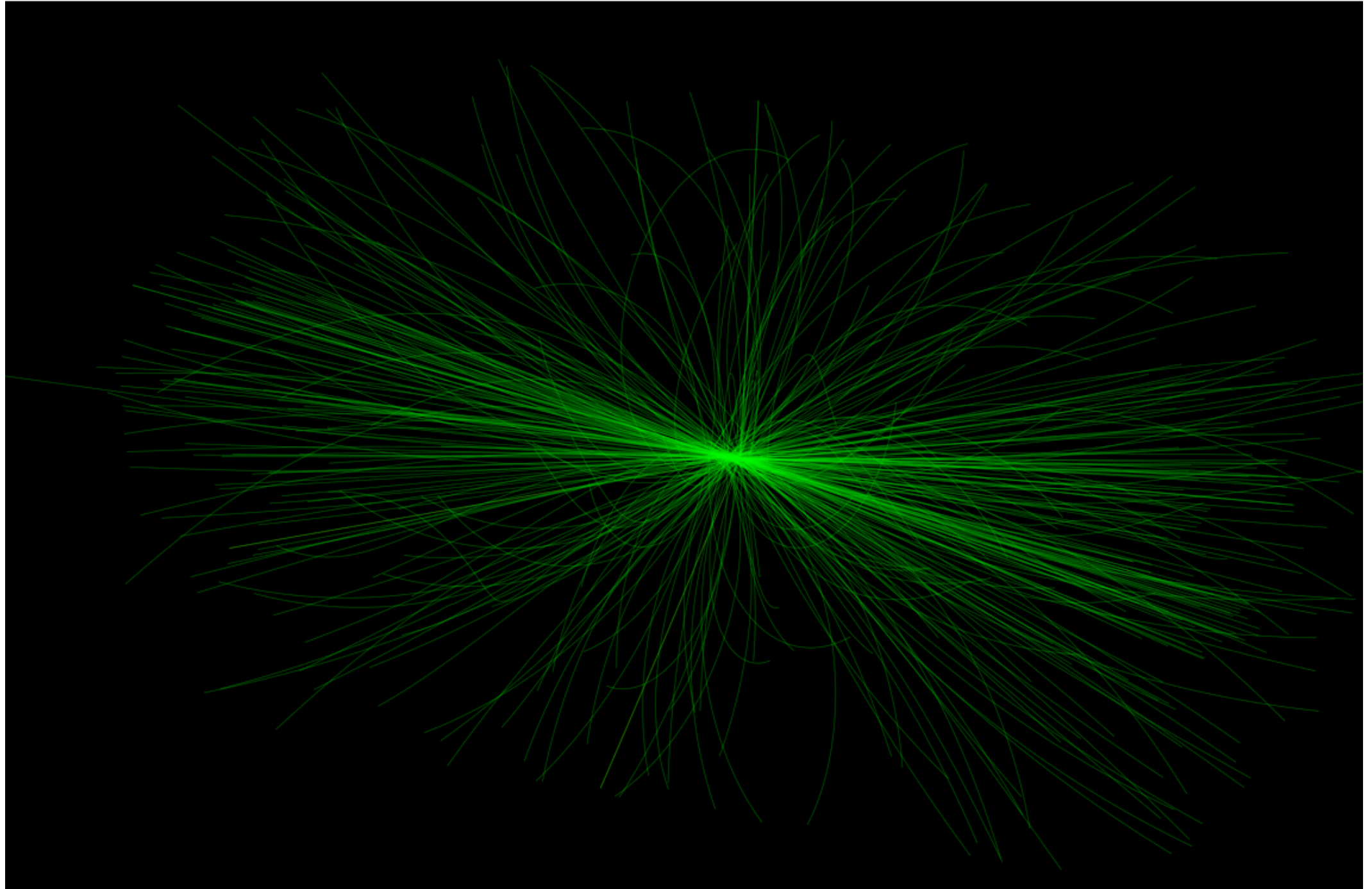


- Theoretiker beschreiben es als
 - ➔ schwer
 - ➔ sehr kurzlebig ($\sim 10^{-22}$ Sekunden)
 - ➔ zerfällt mit Vorliebe in 2 Photonen, 2 Leptonen, 2 quarks oder 2 schwere Eichbosonen (Z,W)

Gebrauchsanweisung für Higgs-Jäger

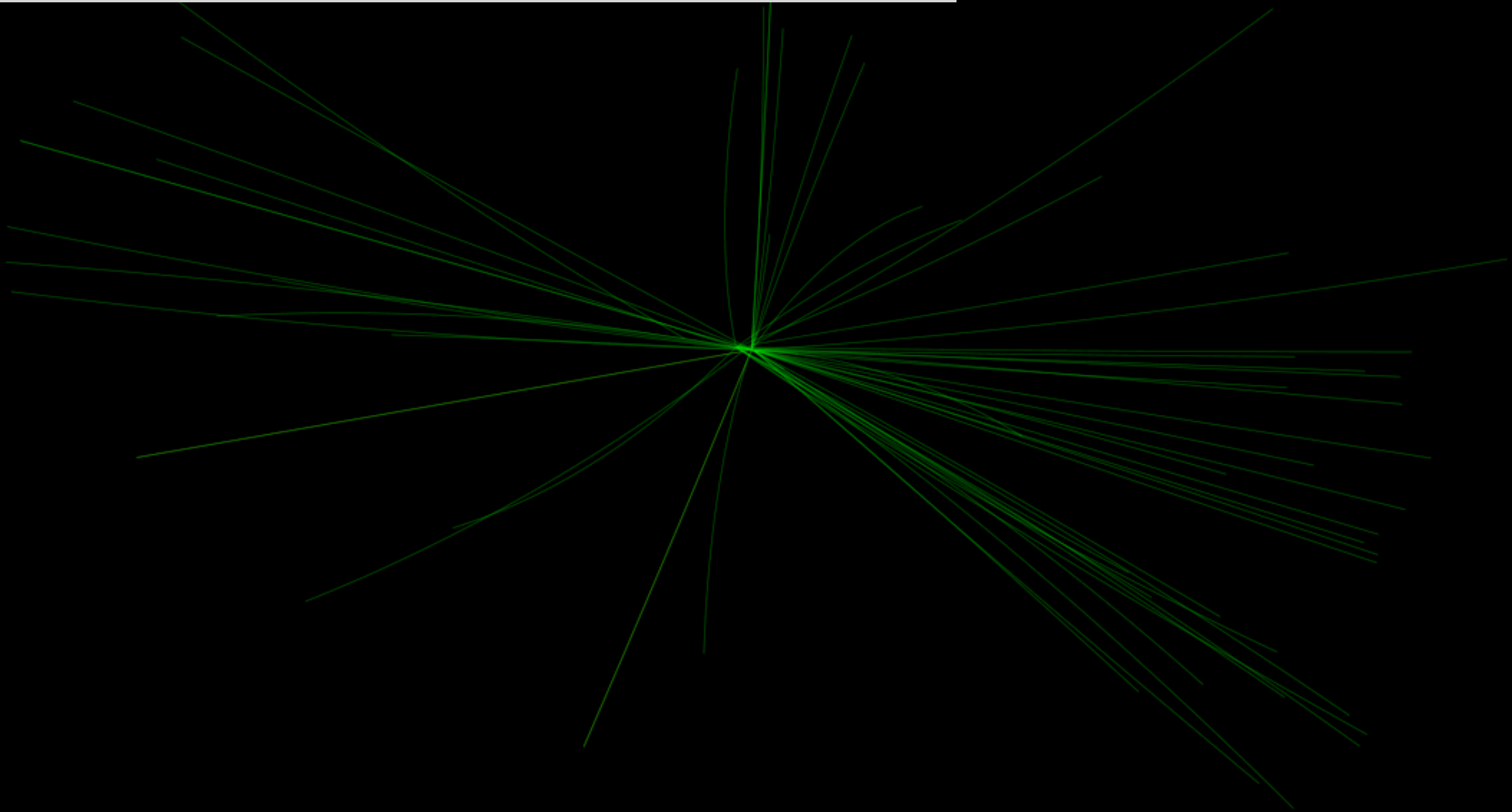
- Baue einen Teilchenbeschleuniger und Collider an dem das Higgs Teilchen erzeugt werden kann;
 - ➔ lasse Teilchen bei sehr hohen Energien zusammenstossen ($E=mc^2$)...
 - ➔ ...und erhöhe die Chance ein Higgs Teilchen zu erzeugen durch viele Kollisionen pro Sekunde ($\sim 10^7$);
- Da das Higgs Teilchen nicht lange lebt, suche nach seinen (stabilen) Zerfallsprodukten;
 - ➔ baue Kameras, die Elektronen, Myonen, Protonen, Neutronen, Pionen, Neutrinos, identifizieren und vermessen können...
 - ➔ ...und die alle Eigenschaften der Teilchen so vermessen können, dass man Higgs Teilchen von den “gewöhnlichen” Teilchen unterscheiden kann.

Higgs Produktion: $p+p \rightarrow H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$



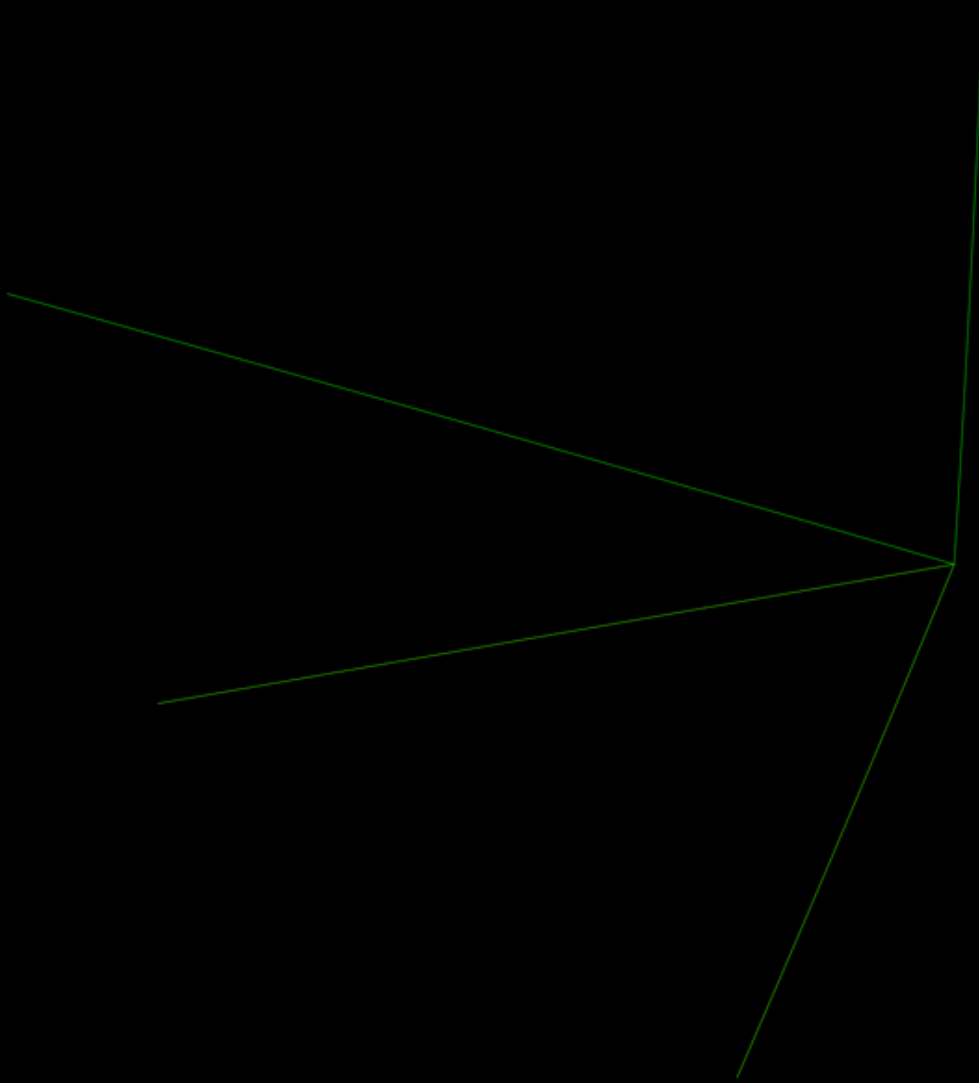
Higgs Produktion: $p+p \rightarrow H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$

Aufräumen: selektiere nur Spuren von
Teilchen, die einen bestimmten Impuls
überschreiten



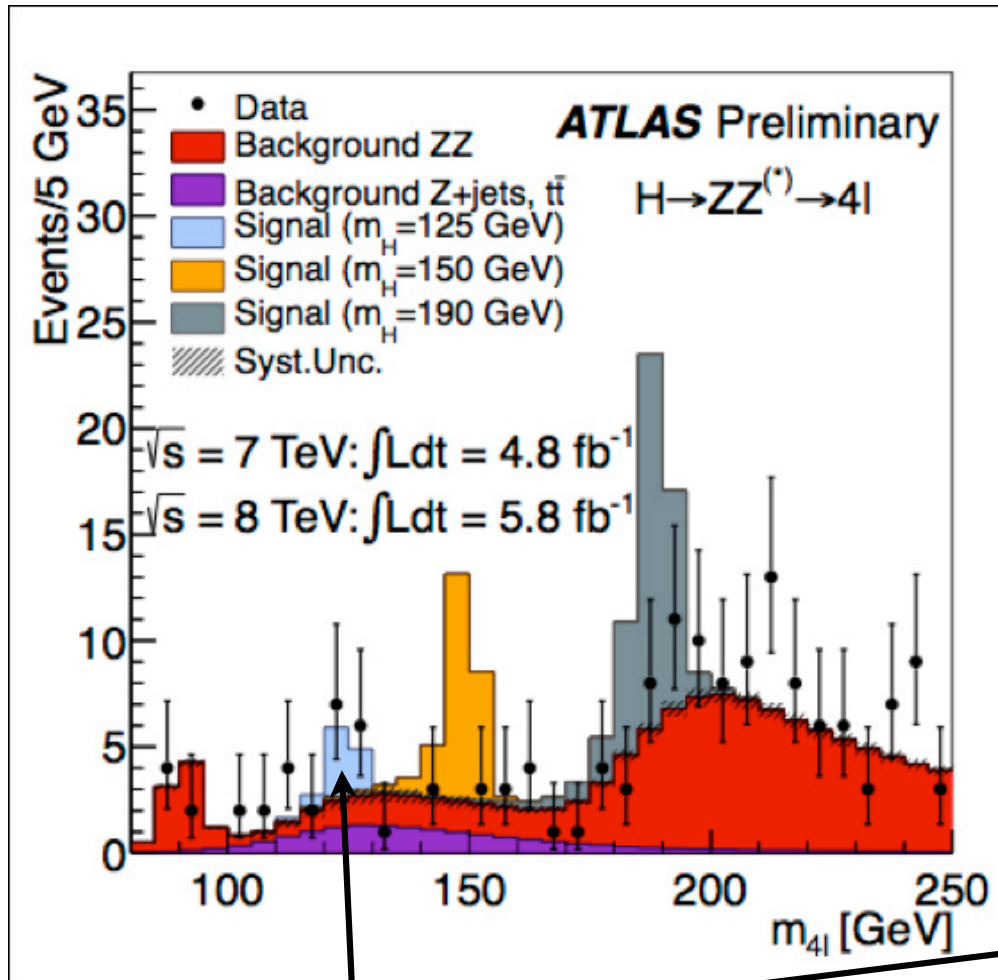
Higgs Produktion: $p+p \rightarrow H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$

...und erhöhe den Impuls-Schnitt...



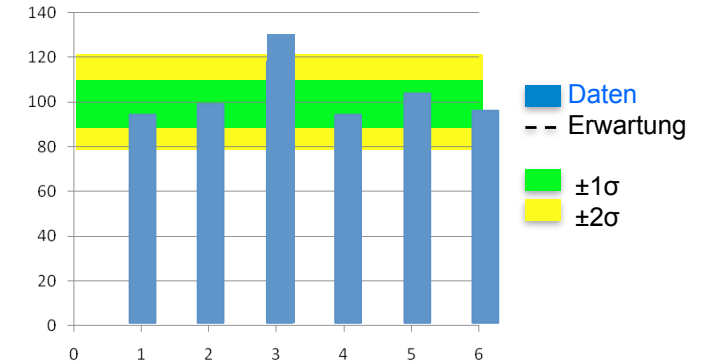
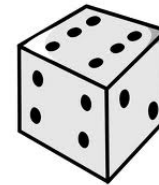
...Voila!!!

Invariante Masse der Objekte, die in 2 Leptonen zerfallen

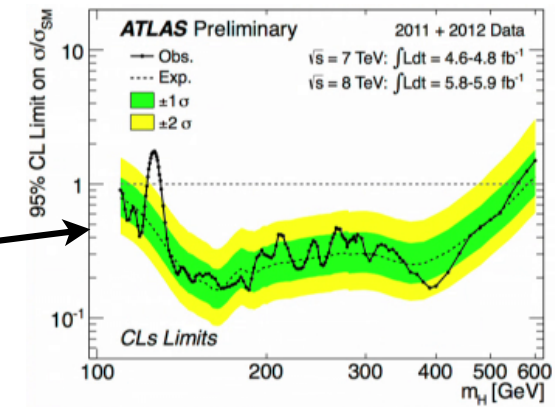


Hier ist das Higgs Teilchen!

Ist der Würfel gezinkt?



Existiert das Higgs Teilchen?



Juli 2012 - ein denkwürdiger Tag

We present updated results on SM Higgs searches based on the data recorded in 2011 at $\sqrt{s}=7$ TeV ($\sim 4.9 \text{ fb}^{-1}$) and 2012 at $\sqrt{s}=8$ TeV ($\sim 5.9 \text{ fb}^{-1}$)

Results are preliminary:

- ❑ 2012 data recorded until 2 weeks ago
- ❑ more challenging conditions in 2012 due to $\sim 2\times$ larger event pile-up
- ❑ new, improved analyses deployed for the first time

$H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$: high-sensitivity at low- m_H ; high mass-resolution; pile-up robust

- ❑ analyses improved to increase sensitivity $\rightarrow$ new results from 2011 data
- ❑ all the data recorded so far in 2012 have been analyzed
- $\rightarrow$ results are presented here for the first time

Other low-mass channels: $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, $H \rightarrow \tau\tau$, $W/ZH \rightarrow W/Z b\bar{b}$:

- ❑ E_{T}^{miss} in final state $\rightarrow$ less robust to pile-up
- ❑ worse mass resolution, no signal "peak" in some cases
- ❑ complex mixture of backgrounds
- $\rightarrow$ understanding of the detector performance and backgrounds in advanced, but results not yet mature enough to be presented to the community
- $\rightarrow$ 2011 results used here for these channels for the overall combination

ATLAS: Status of SM Higgs searches, 4/7/2012



Eine der wichtigsten Folien

We have presented preliminary results on searches for a SM Higgs boson using the full data sample recorded so far for $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ ($\sqrt{s}=7, 8$ TeV, $\sim 10.7 \text{ fb}^{-1}$) and the 2011 data ($\sqrt{s}=7$ TeV, $\sim 4.9 \text{ fb}^{-1}$) for the other channels

Impressive accomplishment of the experiment in all its components: first results with full 2012 dataset were available less than one week from "end of data-taking", with a fraction of good-quality data used for physics of $\sim 90\%$ of the delivered luminosity

We have looked for a SM Higgs over the mass region 110-600 GeV in 12 channels

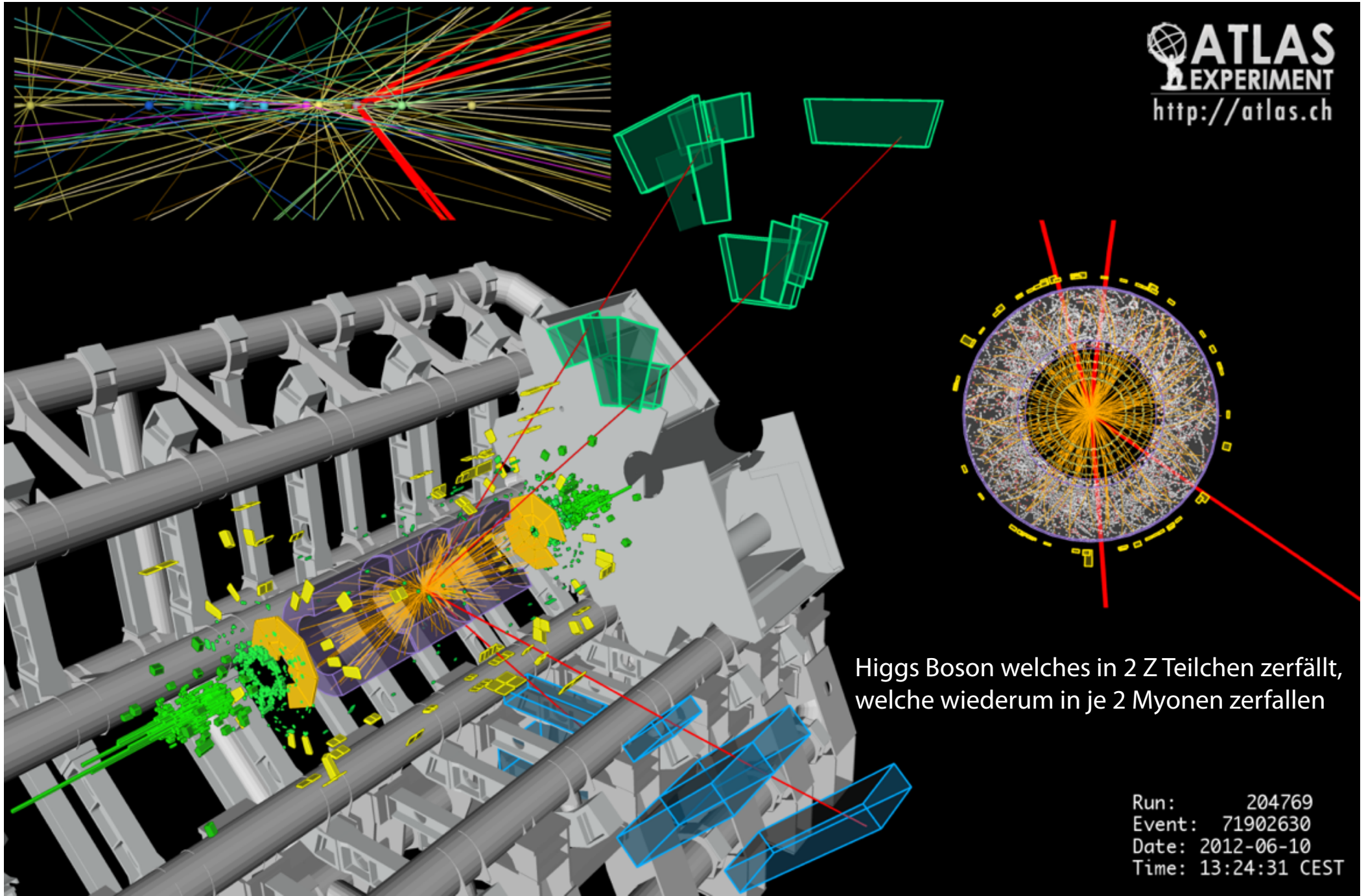
We have excluded at 99% CL the full region up to 523 GeV except $121.8 < m_H < 130.7$ GeV

We observe an excess of events at $m_H \sim 126.5$ GeV with local significance **5.0 σ**

- The excess is driven by the two high mass resolution channels:
 $H \rightarrow \gamma\gamma$ (4.5 σ) and $H \rightarrow ZZ^* \rightarrow 4l$ (3.4 σ)
- Expected significance from a SM Higgs: 4.6 σ
- Fitted signal strength: 1.2 ± 0.3 of the SM expectation

If it is the SM Higgs, it's very kind of it to be at that mass $\rightarrow$ accessible at LHC in $\gamma\gamma$, $ZZ^* \rightarrow 4l$, $WW^* \rightarrow l\nu l\nu$, bb , $\tau\tau$

Wie sieht ein “echtes” Higgs-Ereignis aus?



Higgs Boson welches in 2 Z Teilchen zerfällt,
welche wiederum in je 2 Myonen zerfallen

4. July 2012: CERN special seminar

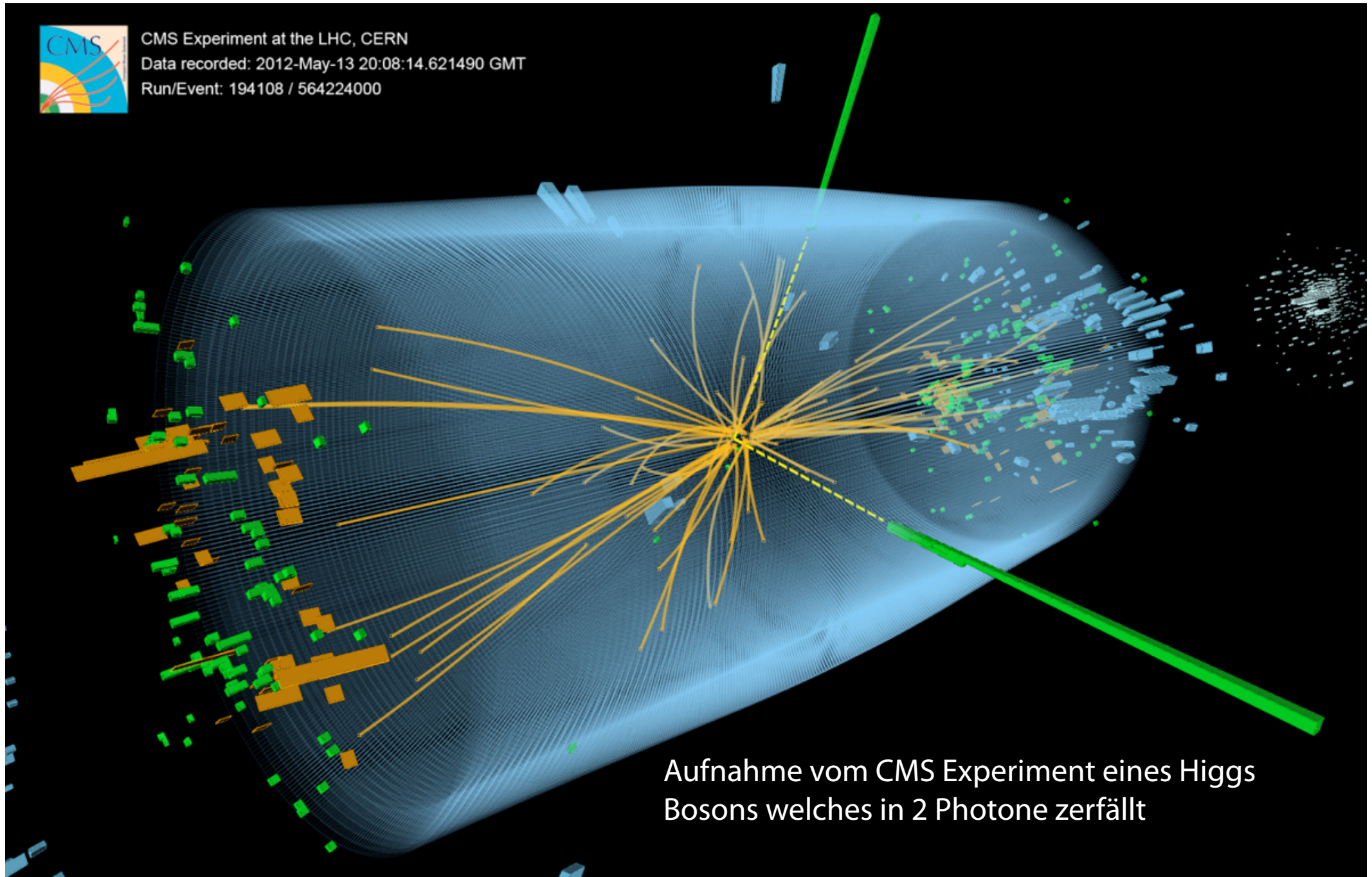
“CERN experiments observe particle consistent with long-sought Higgs boson”



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-13 20:08:14.621490 GMT

Run/Event: 194108 / 564224000



Aufnahme vom CMS Experiment eines Higgs Bosons welches in 2 Photone zerfällt

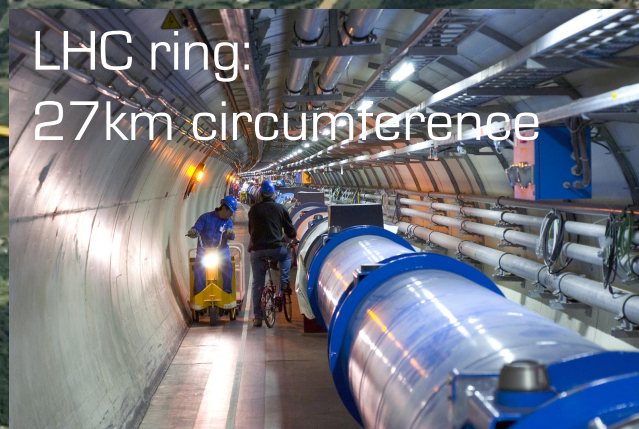
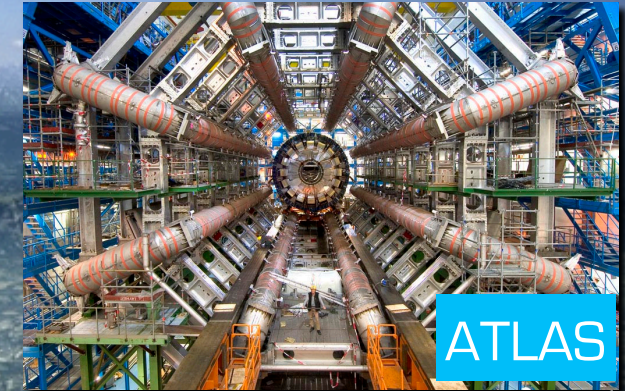
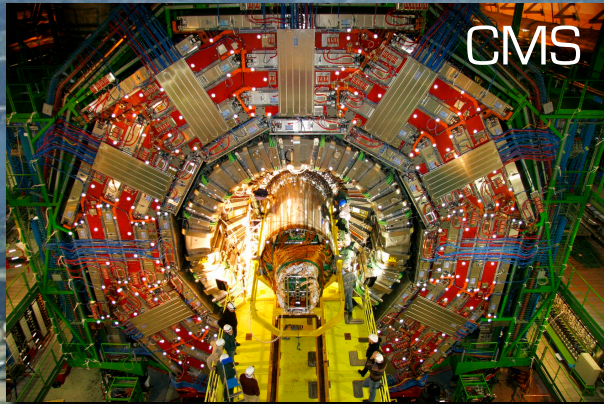
Der Nobelpreis für Physik 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

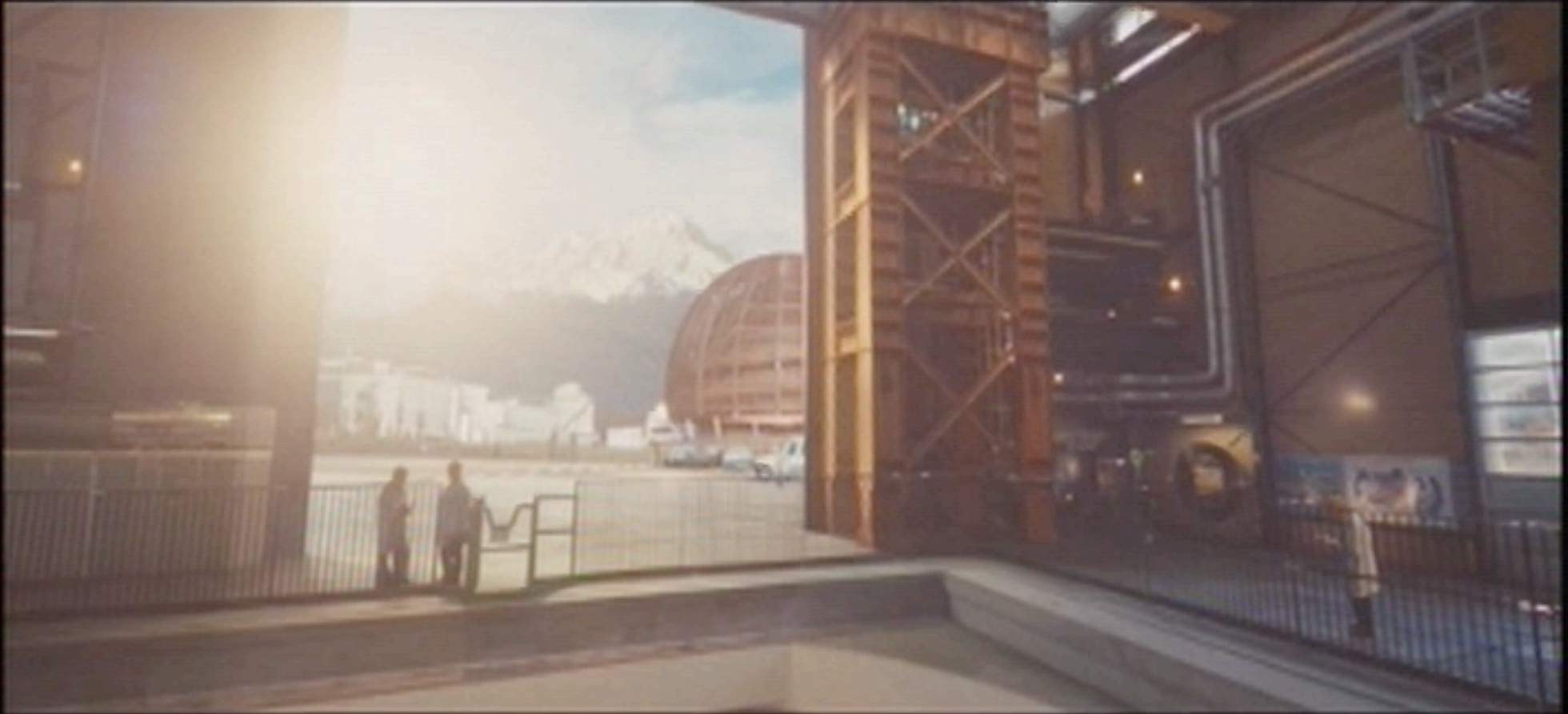


Wo / wie ist eine solche Entdeckung überhaupt möglich?

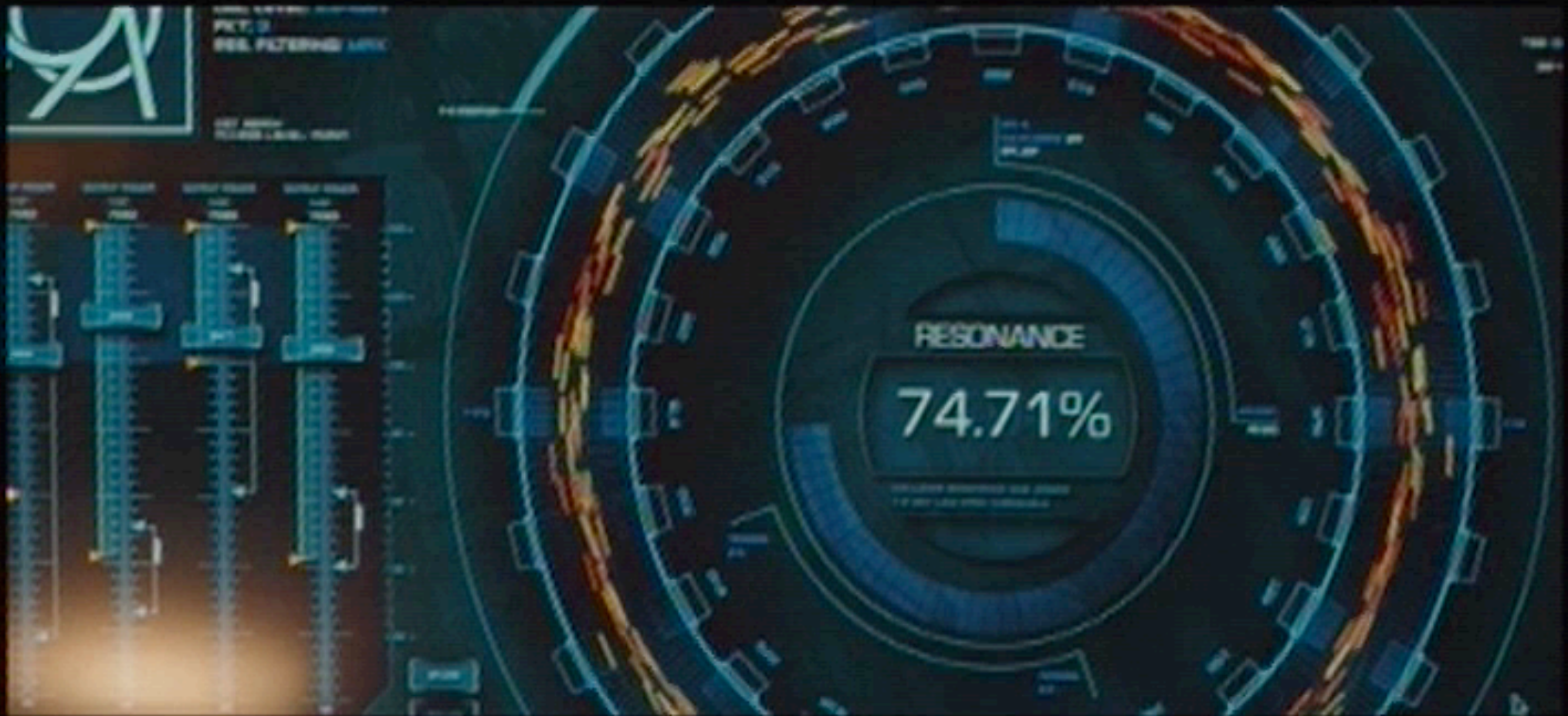
Am CERN!!!



CERN und der Large Hadron Collider (in dem Film “Illuminati”)



CERN und der Large Hadron Collider (in dem Film “Illuminati”)



*Capture should begin
at any moment.*

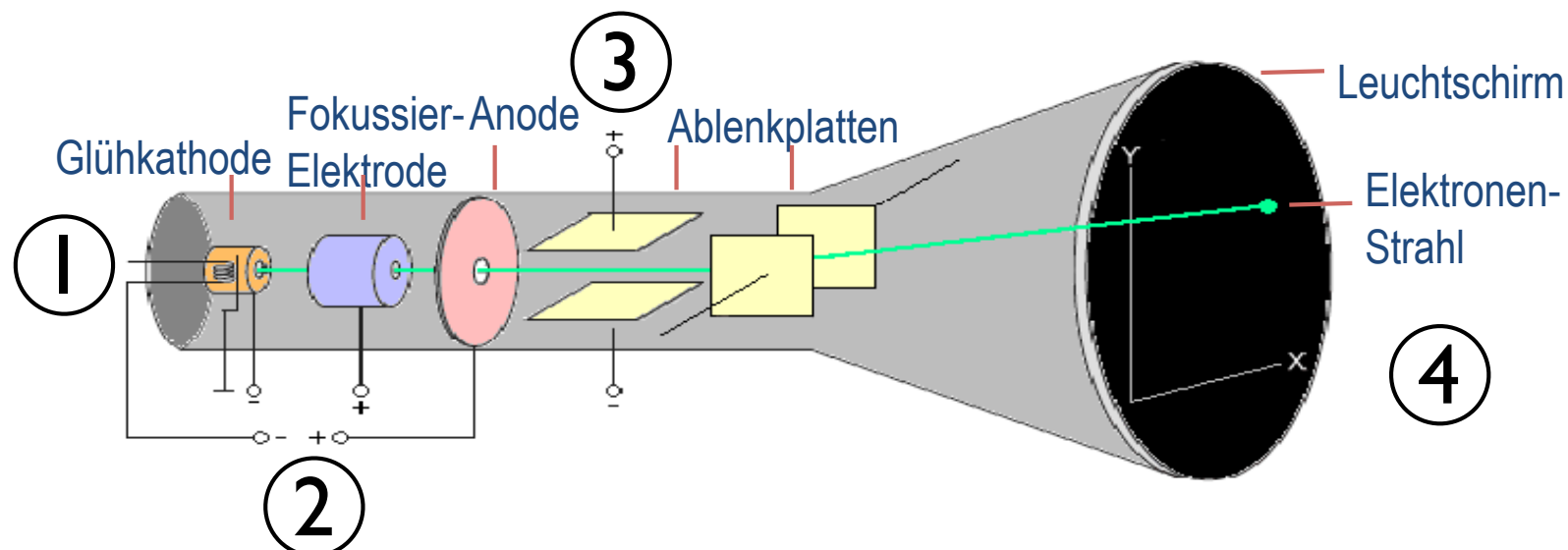
Wie funktioniert ein Beschleuniger?

Ein einfacher Beschleuniger: alter Fernseher (Braun'sche Röhre)



In einem Teilchenbeschleuniger müssen wir...

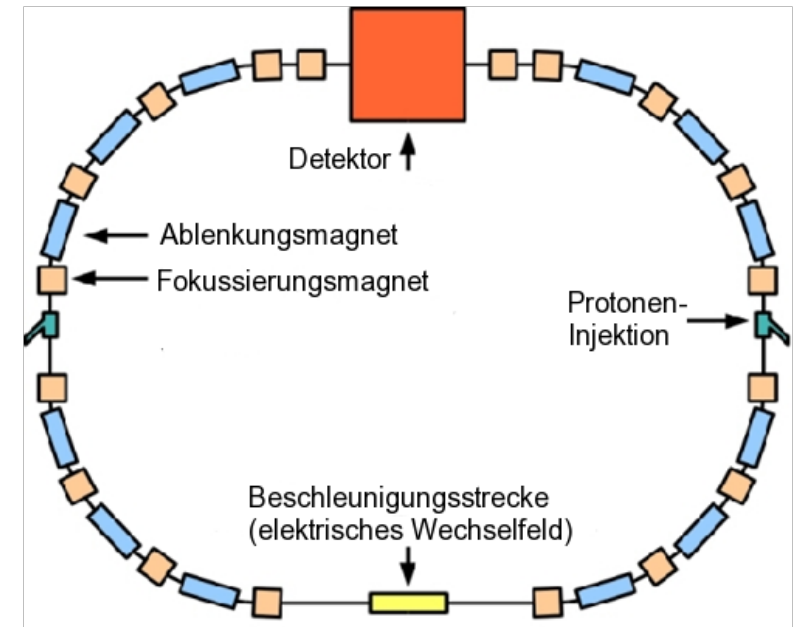
- ①...Teilchen erzeugen, ...
- ②...Teilchen beschleunigen, ...
- ③...Teilchen ablenken und fokussieren, ...
- ④... und die Teilchen detektieren.



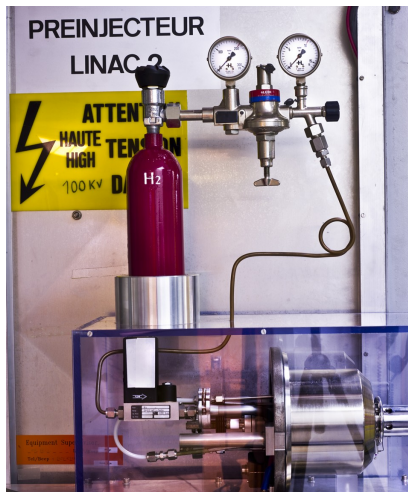
Und wie funktioniert der LHC?

Auch im LHC werden die Protonen...

- ①...erzeugt, ...
- ②...beschleunigt, ...
- ③...ablenkt und fokussiert, ...
- ④... und schließlich zur Kollision gebracht und detektiert.



①



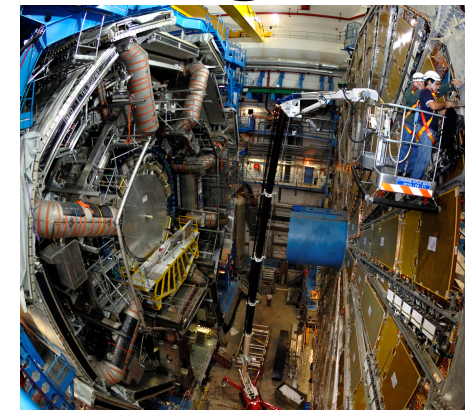
②



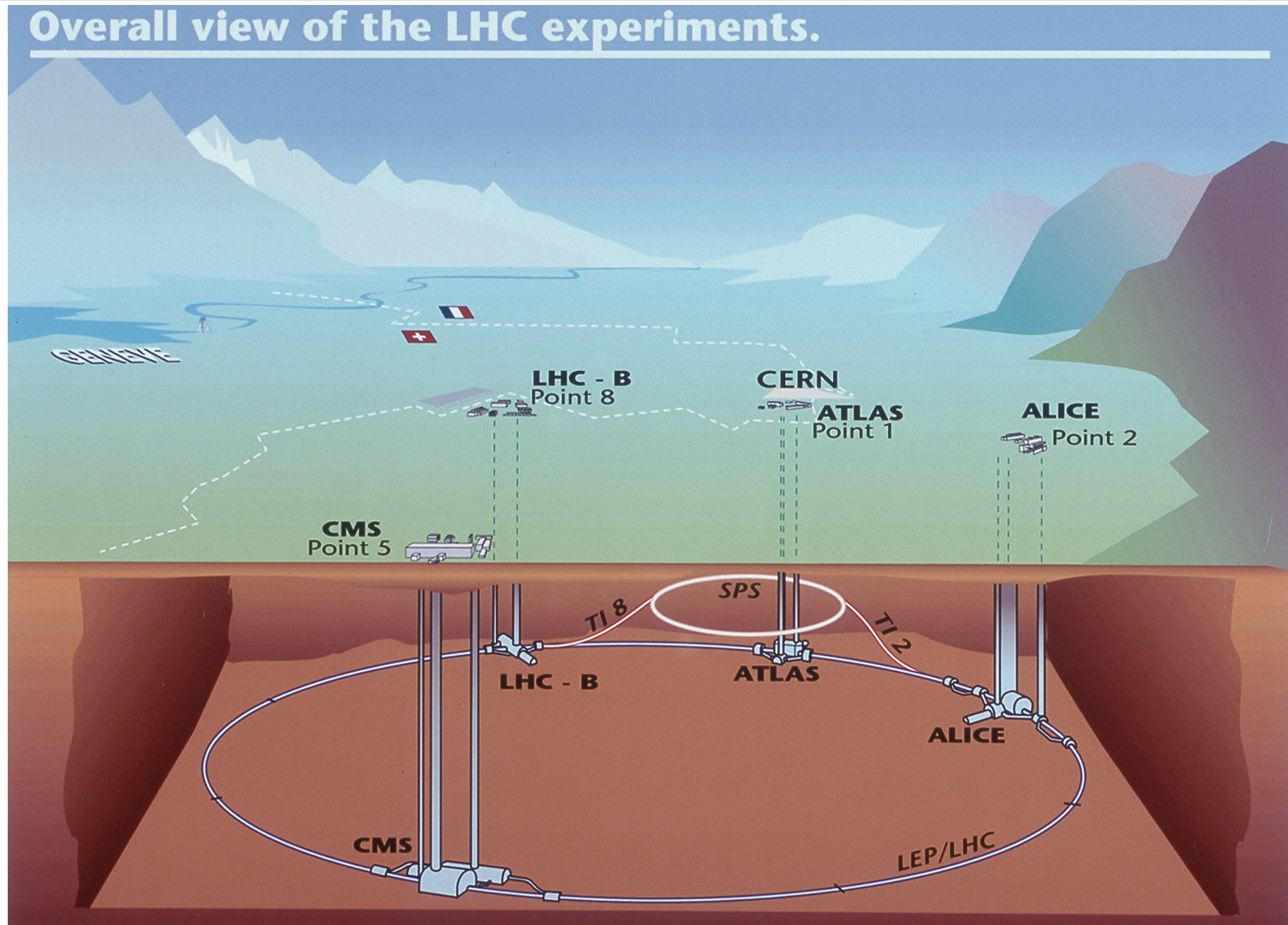
③



④



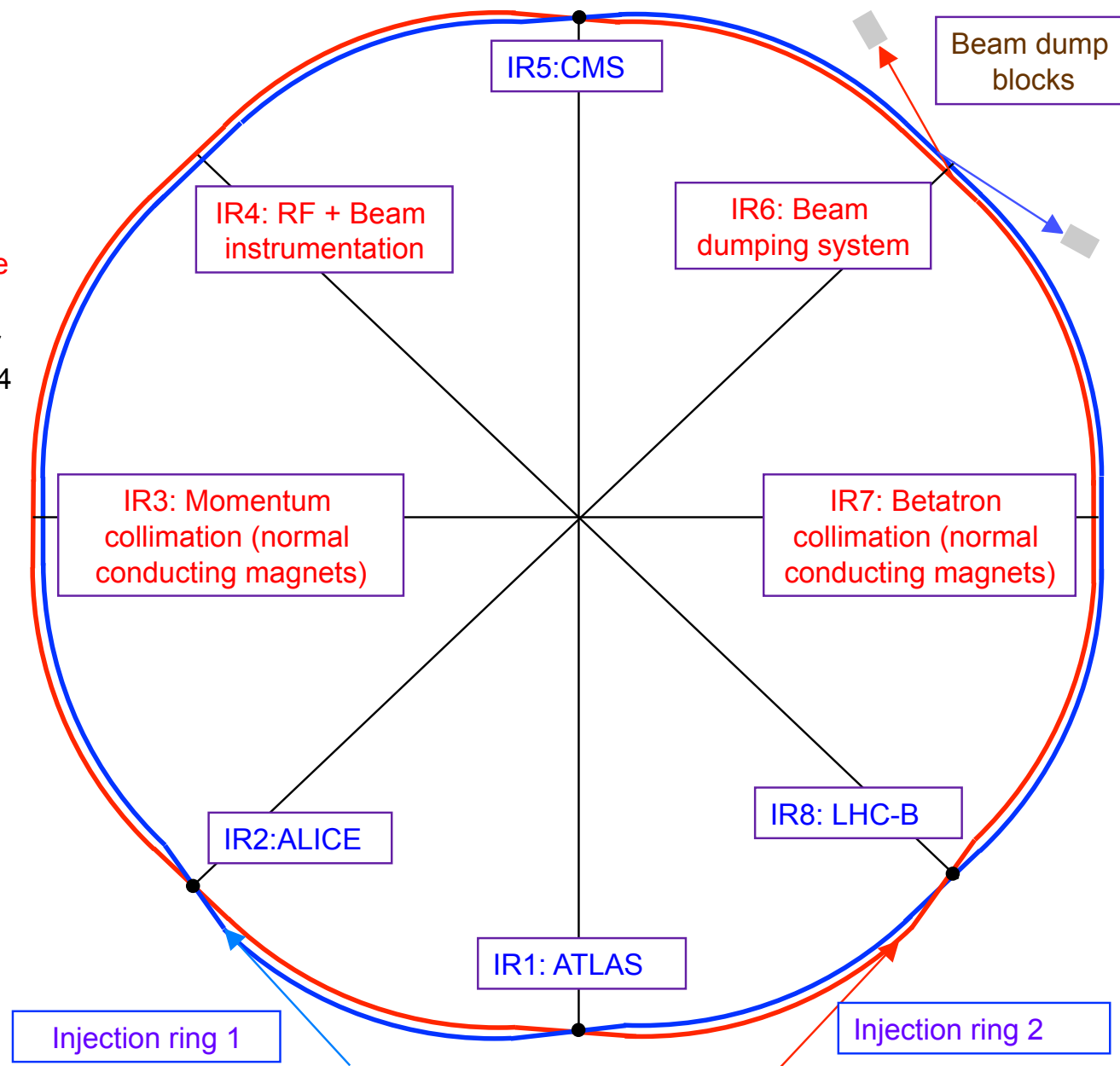
Der LHC am (unter dem) CERN



Das LHC Layout

- 8 arcs.
- 8 long straight sections (insertions), ~ 700 m long.
- beam 1 : clockwise
- beam 2 : counter-clockwise
- The beams exchange their positions (inside/outside) in 4 points to ensure that both rings have the same circumference !

The main dipole magnets define the geometry of the circle !



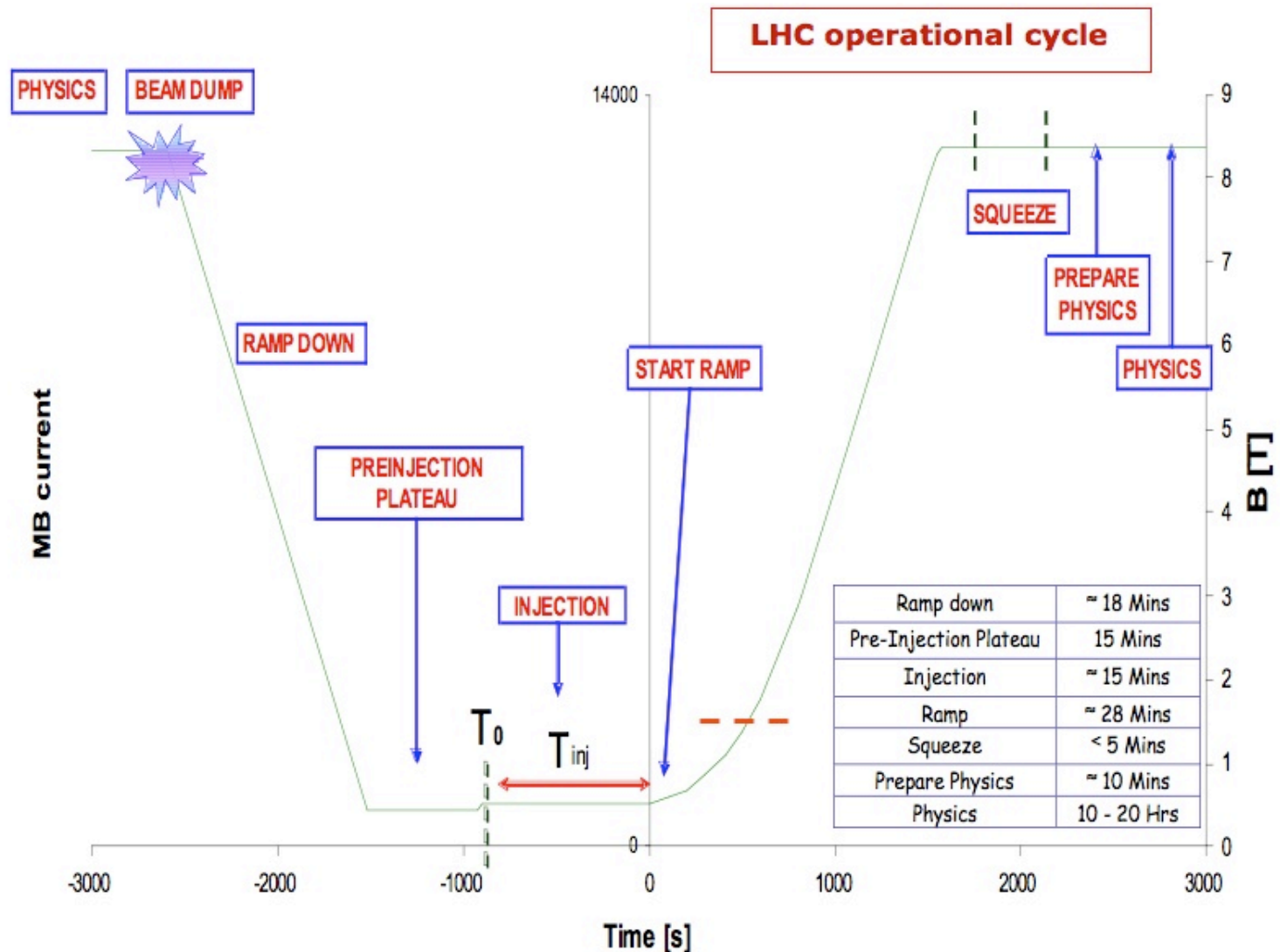
Ein Blick in den LHC Tunnel



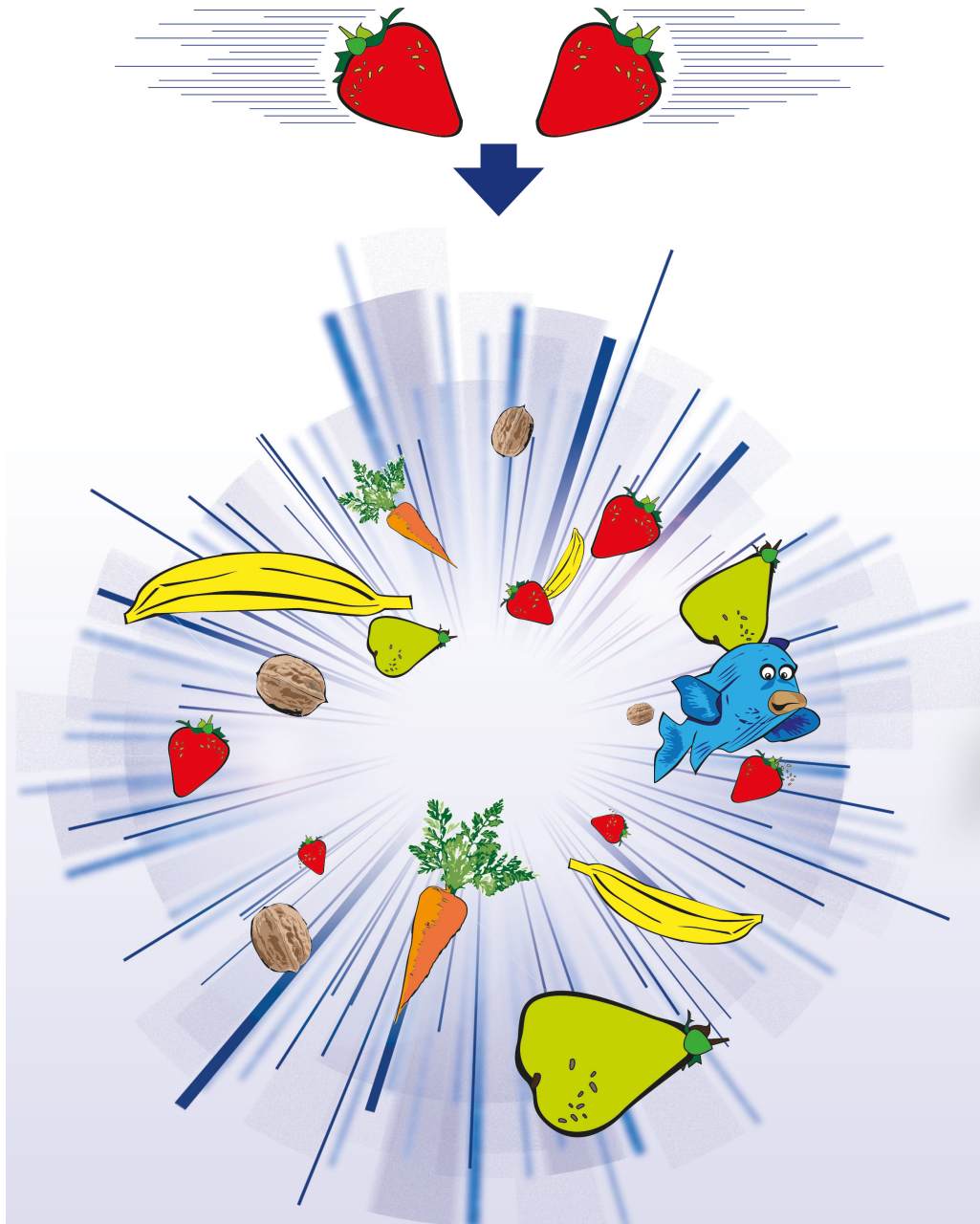
Wie sieht ein LHC “Run” aus?

- Der LHC läuft tagein/tagaus, 40 Millionen Strahlkollisionen pro Sekunde
- Die Energie der Protonen eines Strahls ist 4 TeV ab 2015: 7 TeV!

Sind die Protonen “verbraucht”, wird der LHC erneut gefüllt; ~1 mal pro Tag



Was passiert bei einer Kollision?



Bei Teilchenkollisionen wandelt sich ein Teil der Bewegungsenergie in Masse um.

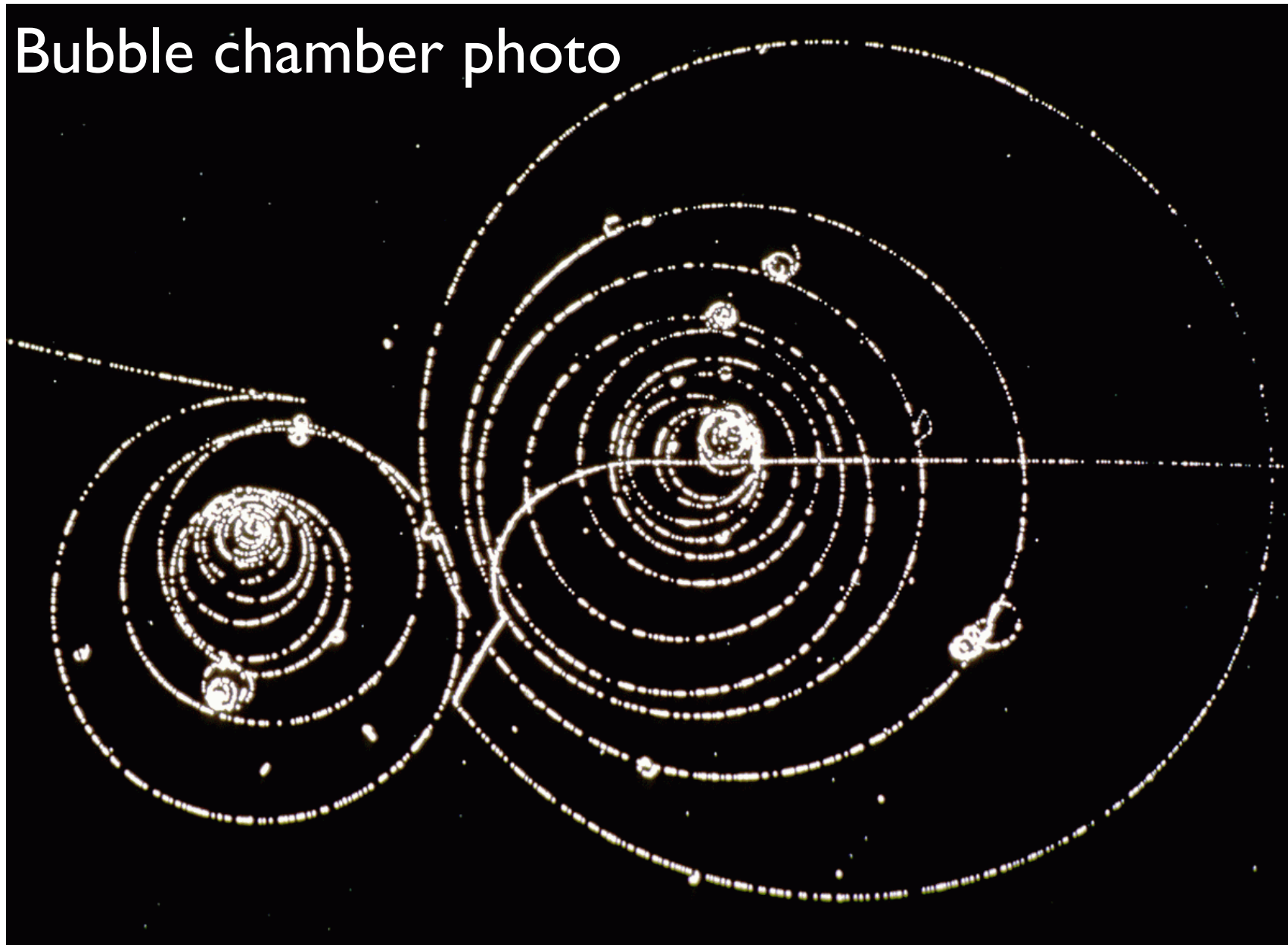
Dabei werden **völlig neue Teilchen** erzeugt...
...diese waren vorher keine Teile der Protonen!

Manchmal entstehen auch exotische Teilchen...!

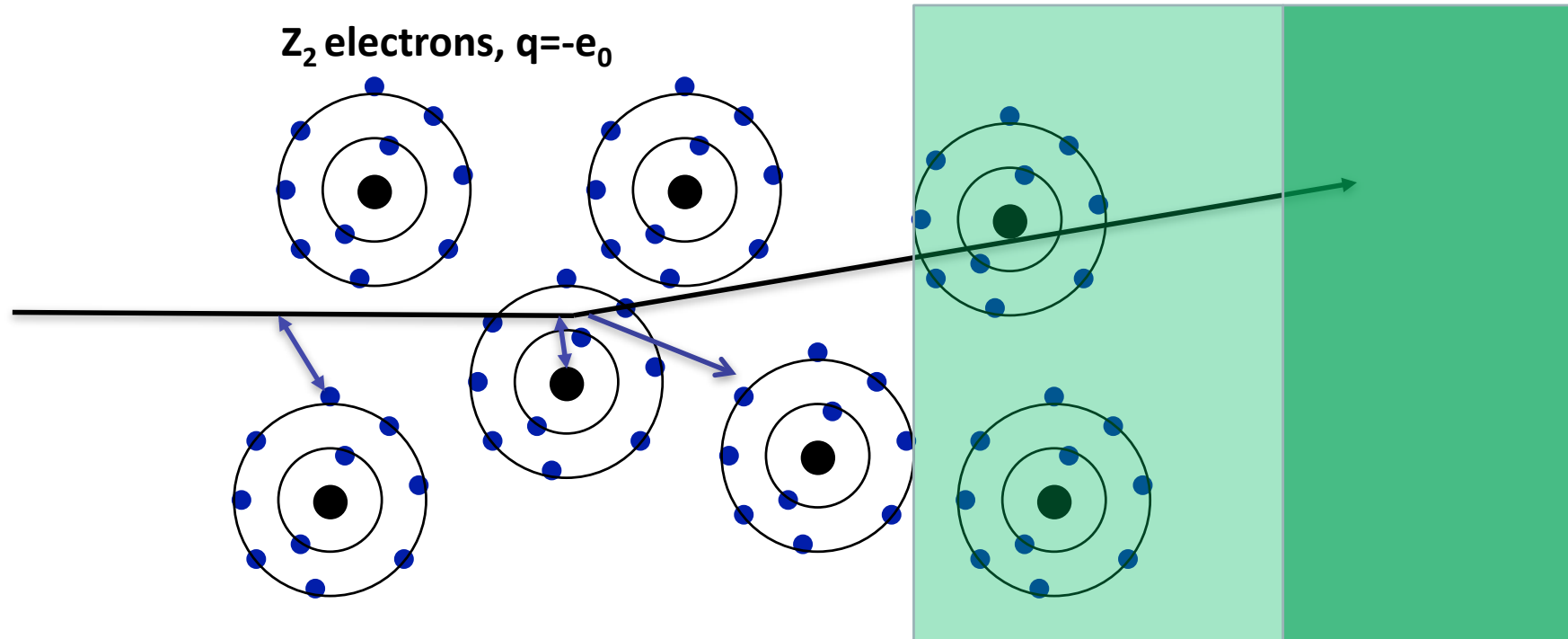
Detektoren - Ein (grober) Überblick

Ein wunderschönes Bild, aufgenommen von einem Teilchendetektor

Bubble chamber photo



Electromagnetische Wechselwirkung eines Teilchens mit Materie



Wechselwirkung mit den Elektronen der Atome. Das Teilchen verliert Energie und die Atome werden angeregt oder ionisiert

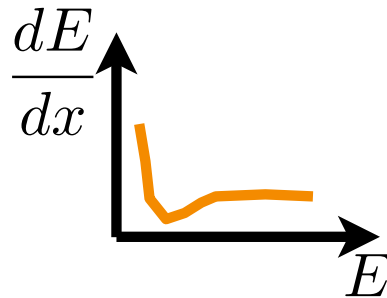
Wechselwirkung mit dem Atomkern. Das Teilchen wird abgelenkt (gestreut), daraus folgt Vielfachstreuung im Material. Beim Streuprozess kann ein Bremsstrahlungsphoton abgestrahlt werden.

Wenn die Geschwindigkeit des Teilchens schneller ist als die Lichtgeschwindigkeit in dem Material, dann gibt es elektromagnetische “Schockwellen”, Cherenkov Licht. Wenn das Teilchen Grenzflächen zwischen verschiedenen Medien durchquert, kann ein Übergangsstrahlungsphoton abgestrahlt werden.

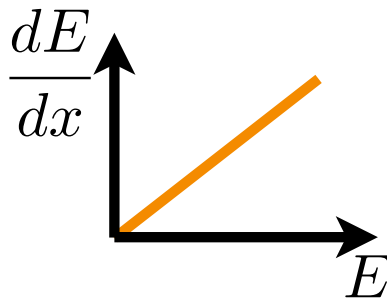
Wechselwirkung von Teilchen in Materie: eine Zusammenfassung

e^+/e^-

Ionisation

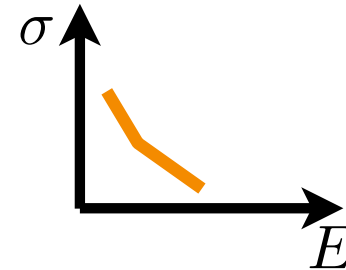


Bremsstrahlung

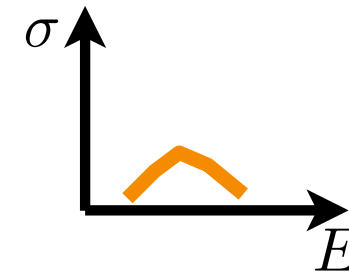


γ

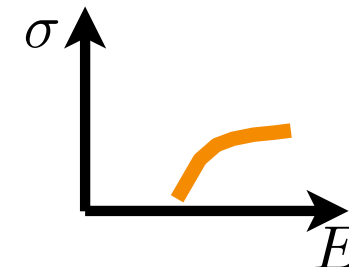
Photoelektrischer Effekt



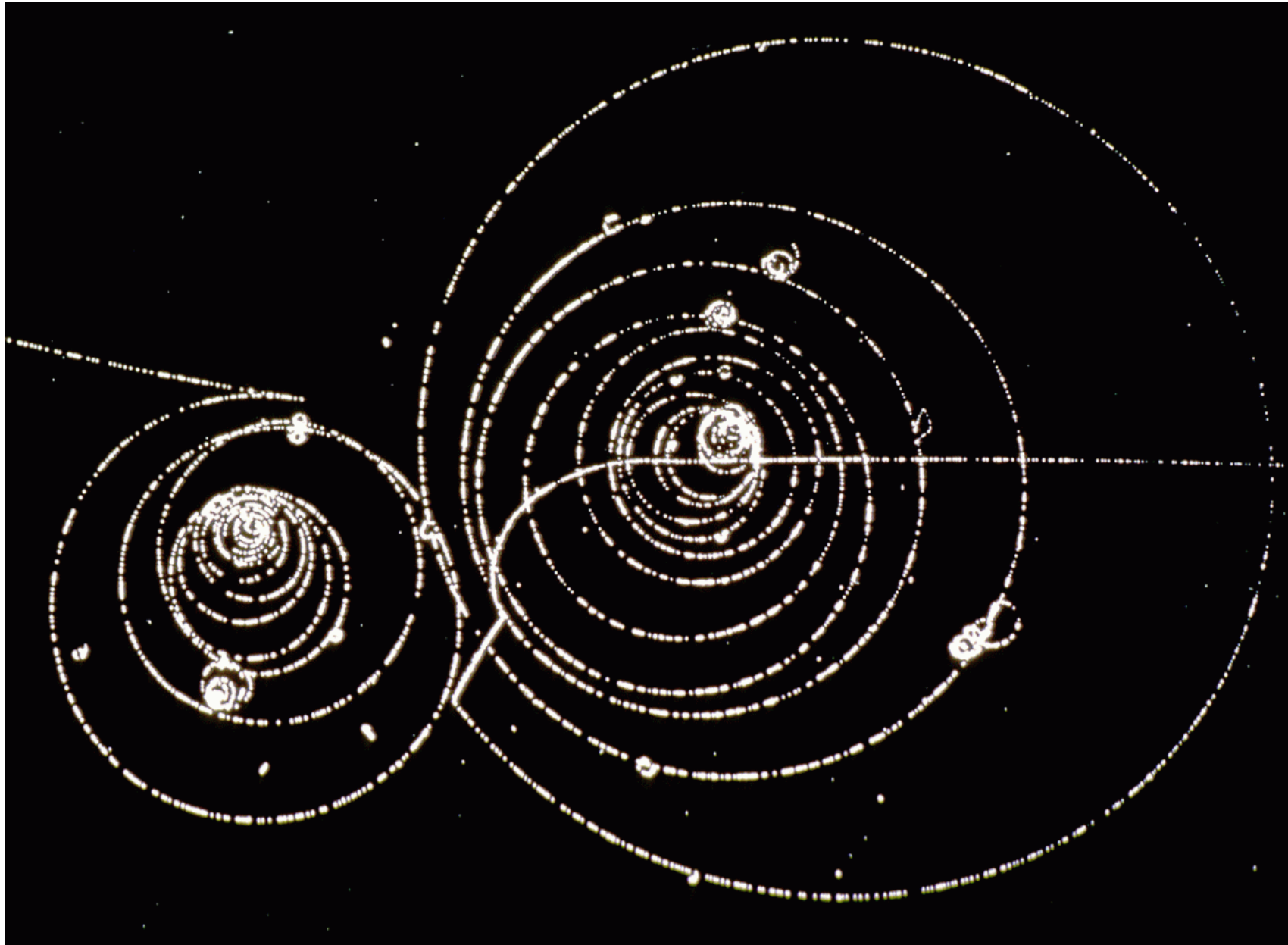
Compton Effekt



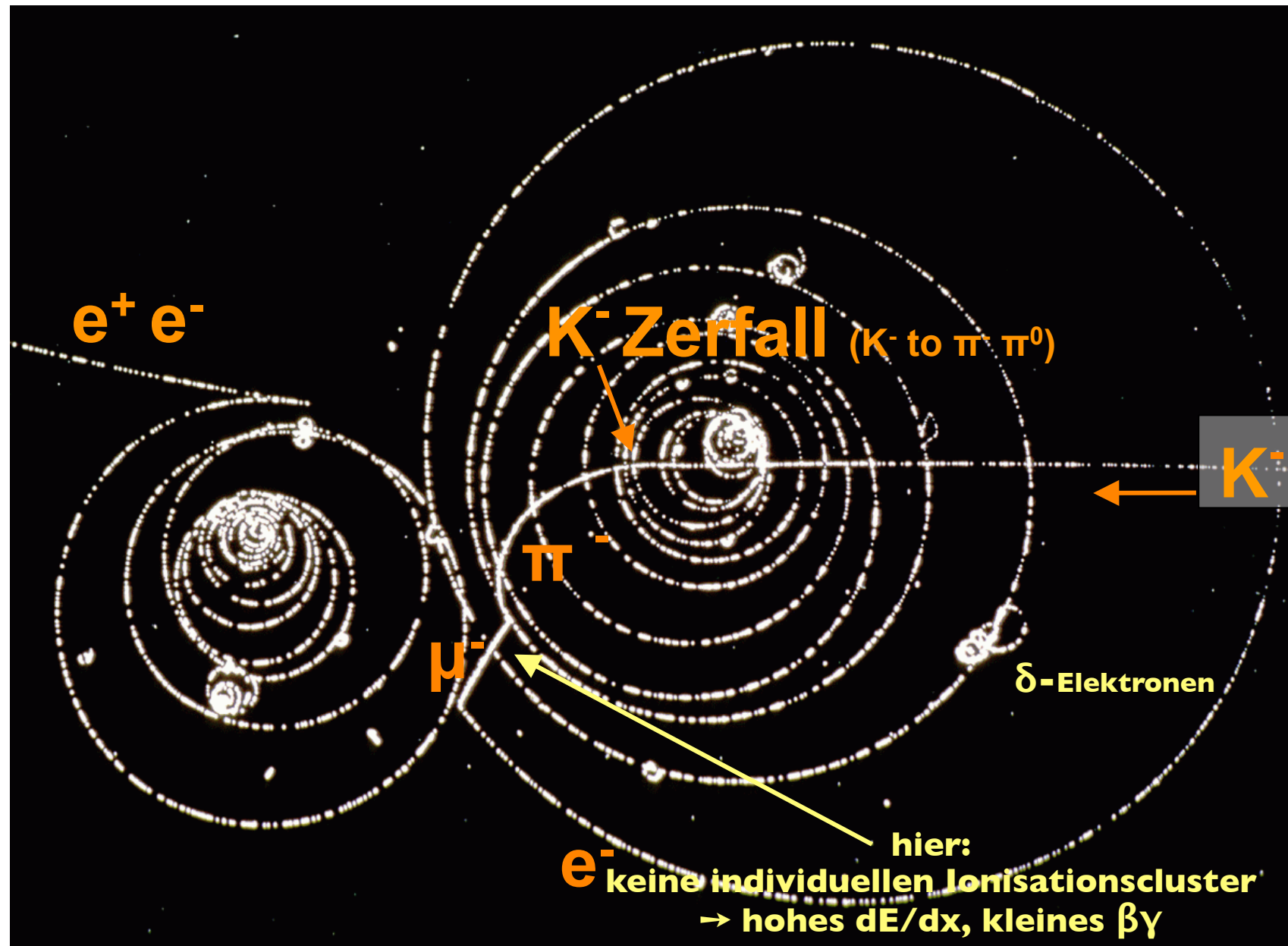
Paar-Produktion



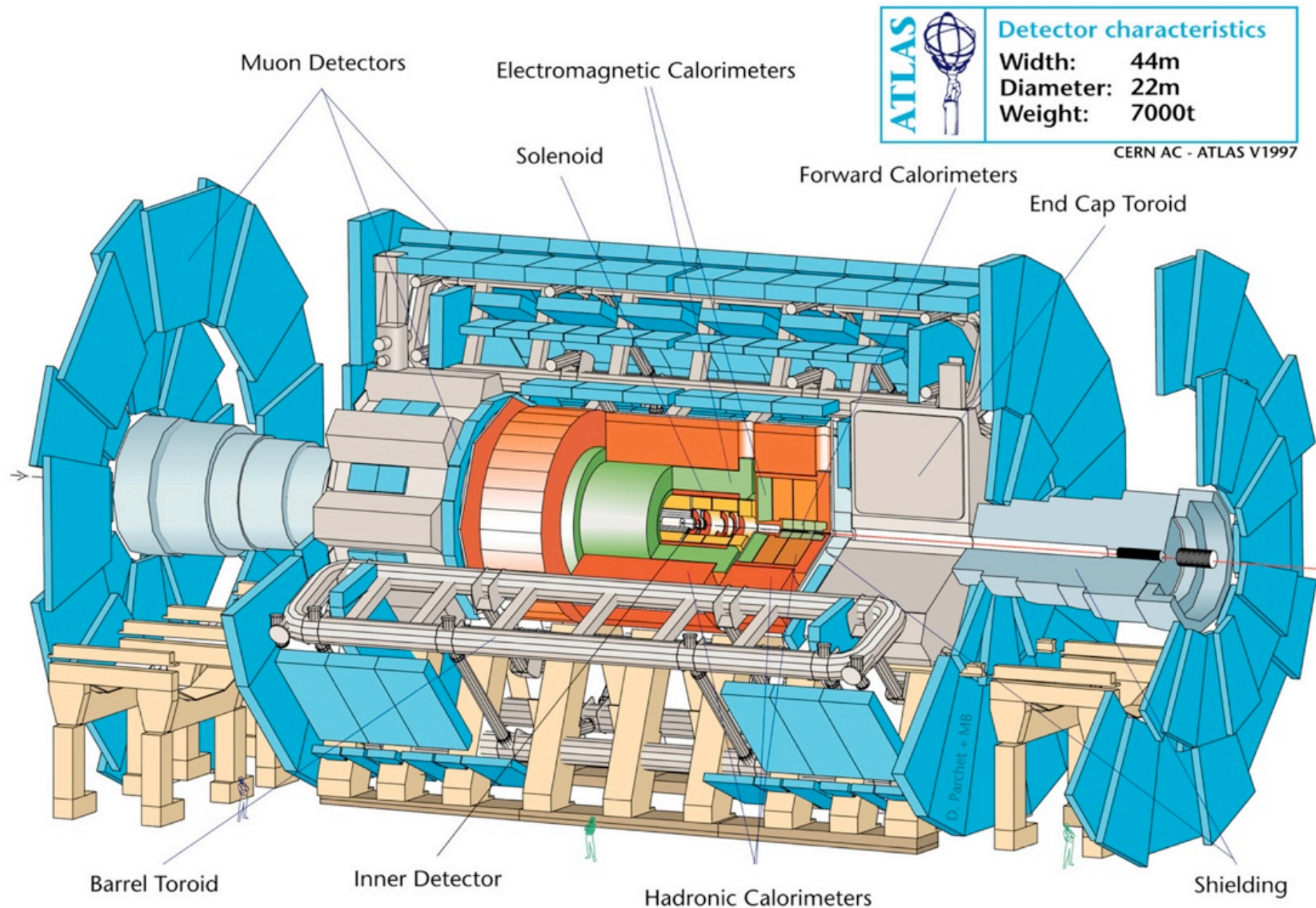
...und jetzt wissen Sie genau was Sie hier sehen. Oder?



JETZT wissen Sie's...

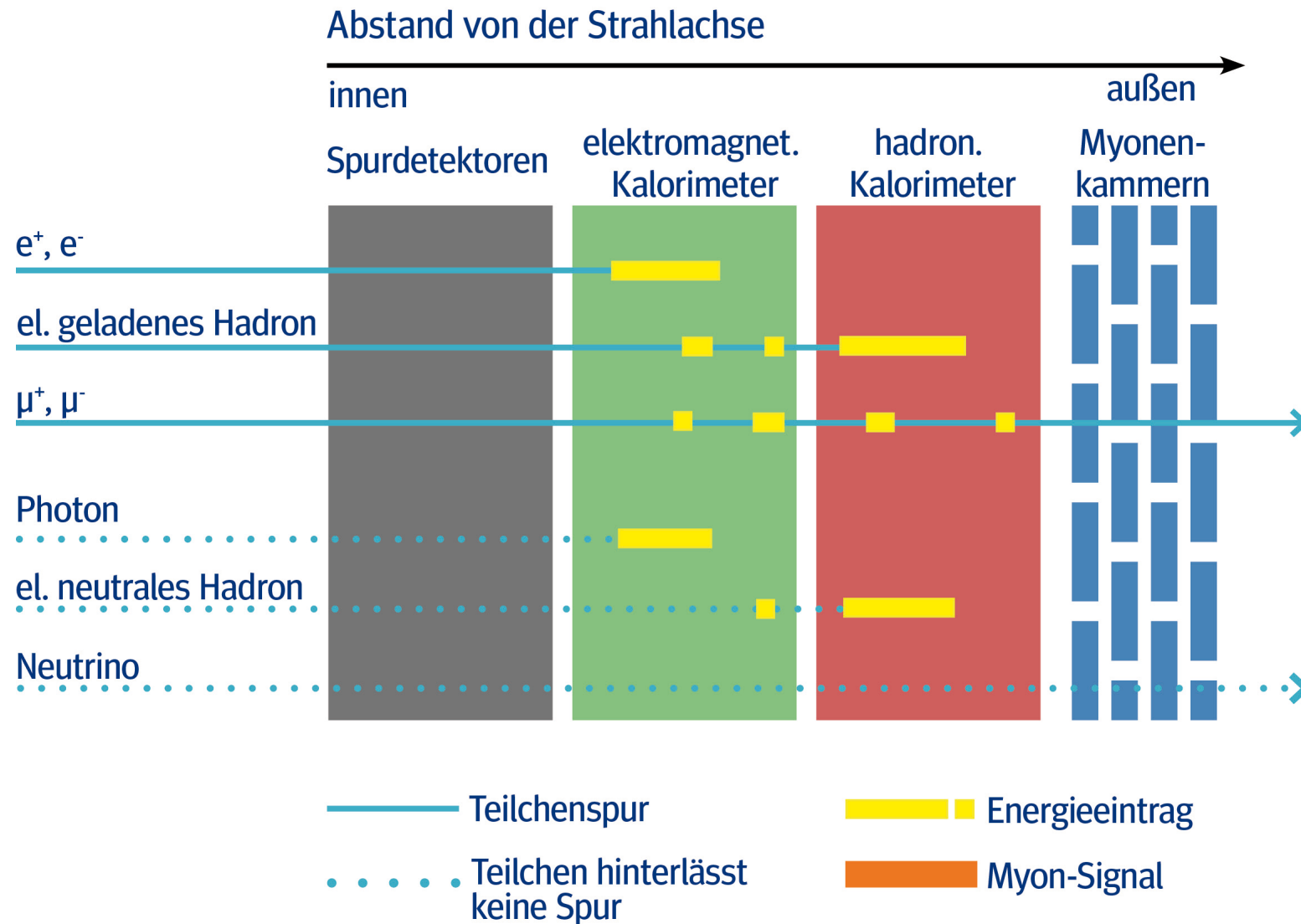


Ein Beispiel eines LHC Teilchendetektors: ATLAS



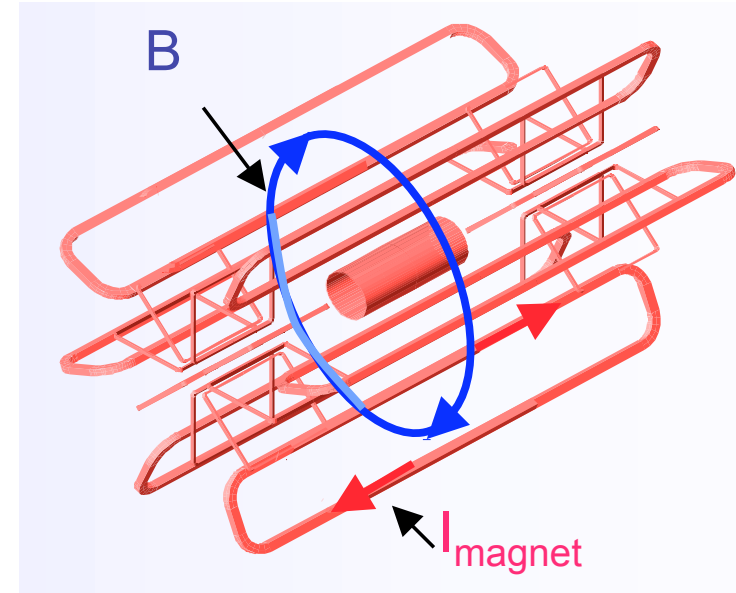
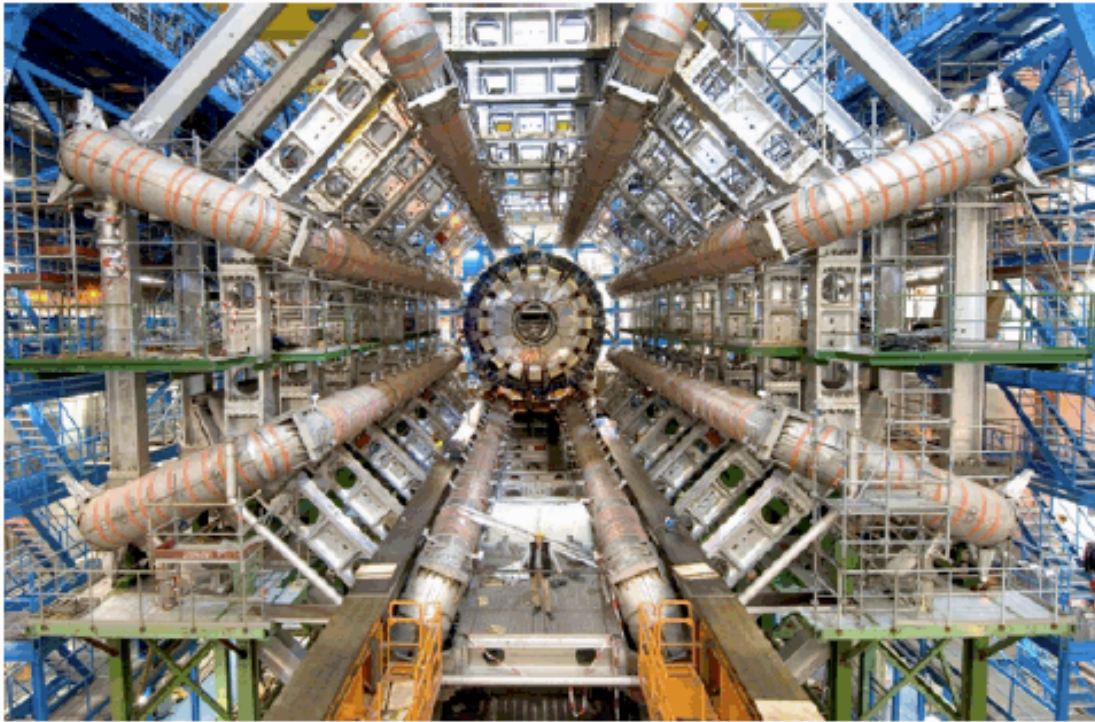
Teilchensignaturen in einem Detektor

Beispiel: der ATLAS Detektor



Magnet concept: ATLAS $\Rightarrow$ toroid

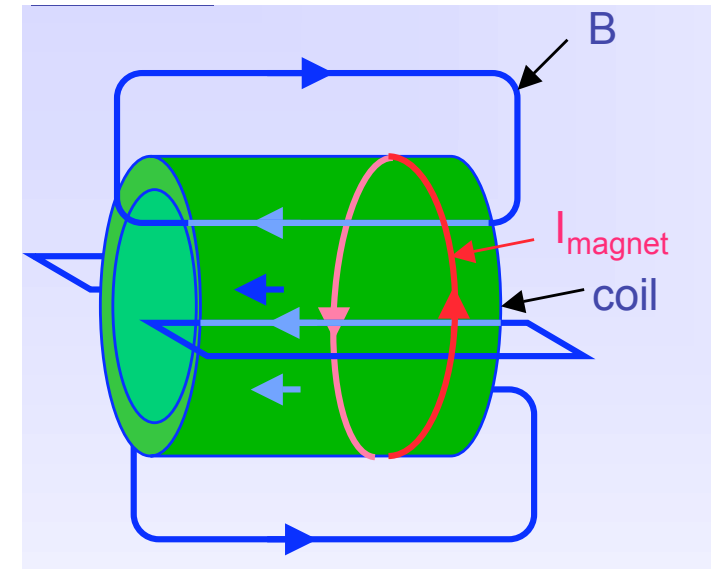
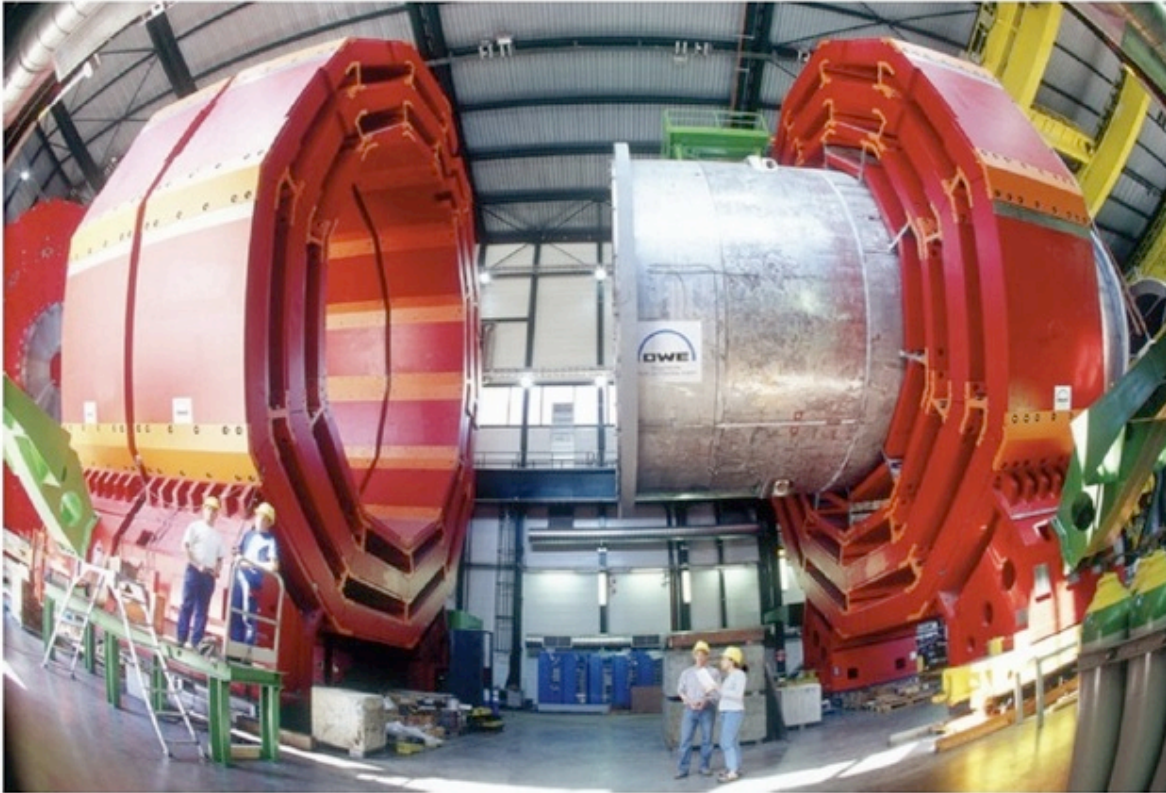
the largest magnet in the world



- Central Toroid field within Muon-System: 4 T
 - Closed field, no yoke
 - Complex field
- 2 T Solenoid-field for trackers

- + field always perpendicular to p_T
- + relative large field over large volume
- non uniform field
- complex structure

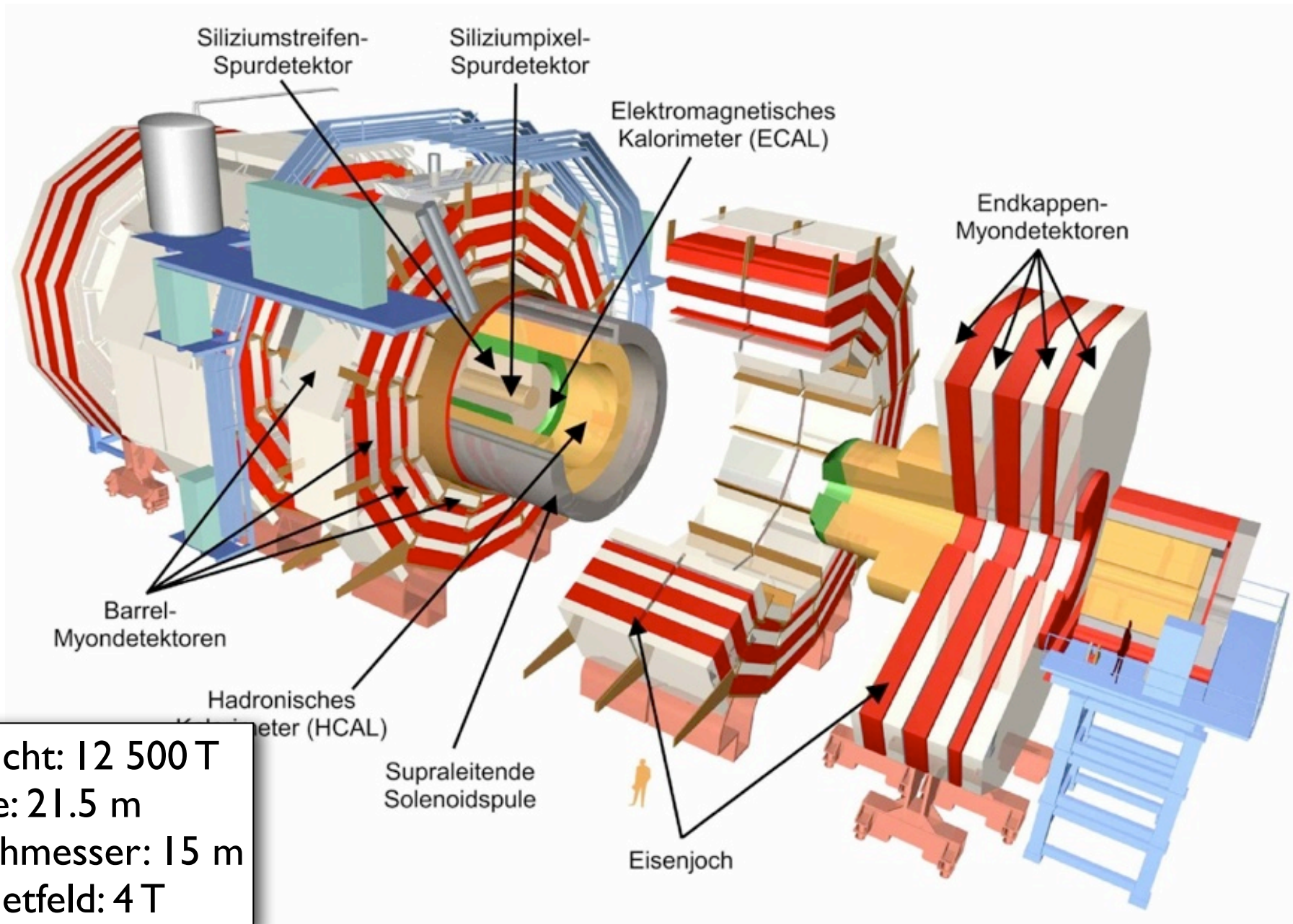
Magnet concept: CMS $\Rightarrow$ one solenoid



- Largest Solenoid in the world:
 - superconducting, 4 T field
 - encloses trackers and calorimeter
 - 13 m long, inner radius 5.9 m, $I = 20$ kA, weight of coil: 220 t

- + large homogeneous field inside coil
- + weak opposite field in return yoke
- size limited (cost)
- relative high material budget

CMS: der “schwere” Detektor

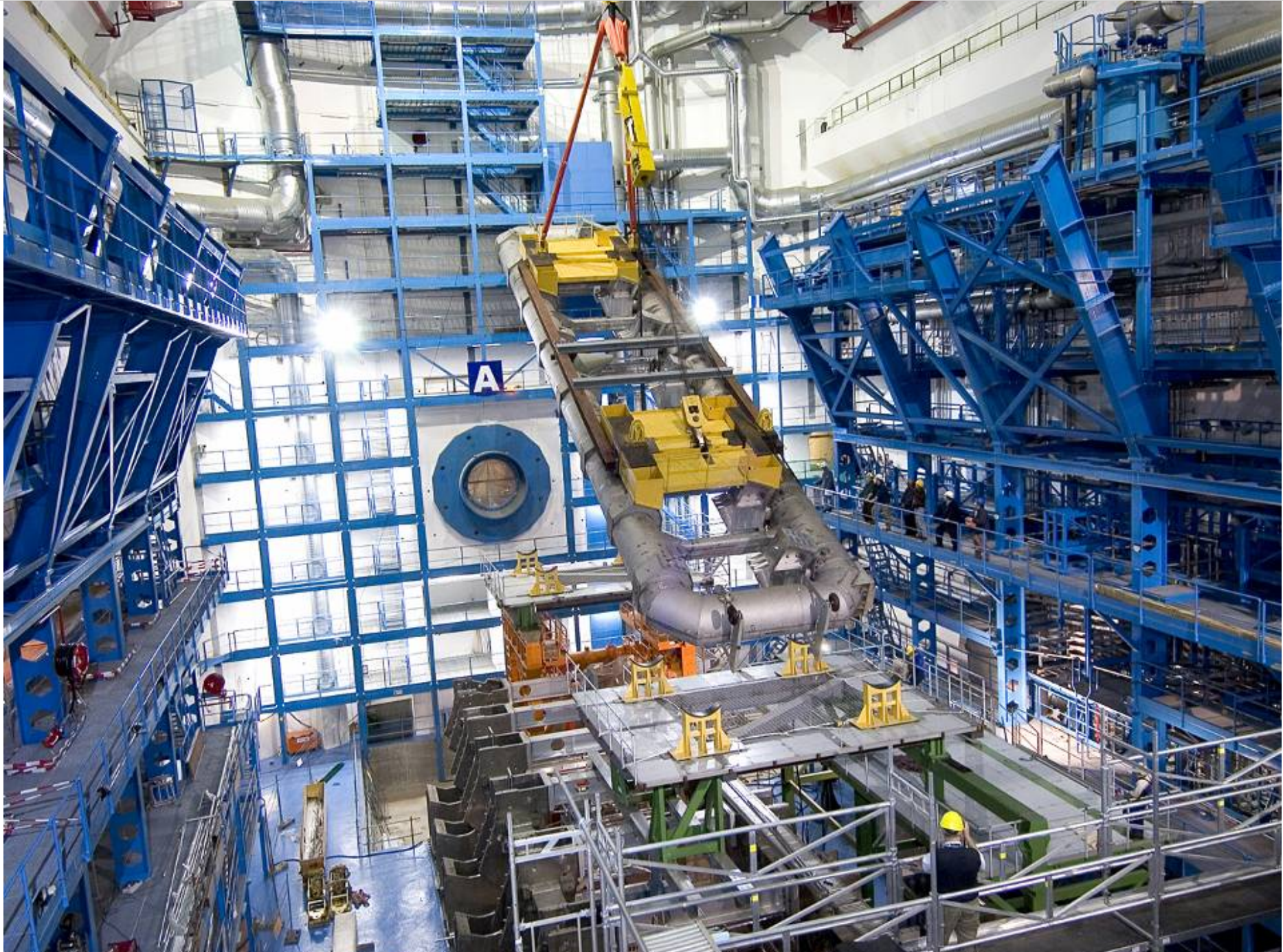


Gewicht: 12 500 T
Länge: 21.5 m
Durchmesser: 15 m
Magnetfeld: 4 T

Der Bau des ATLAS Detektors



Der Bau des ATLAS Detektors



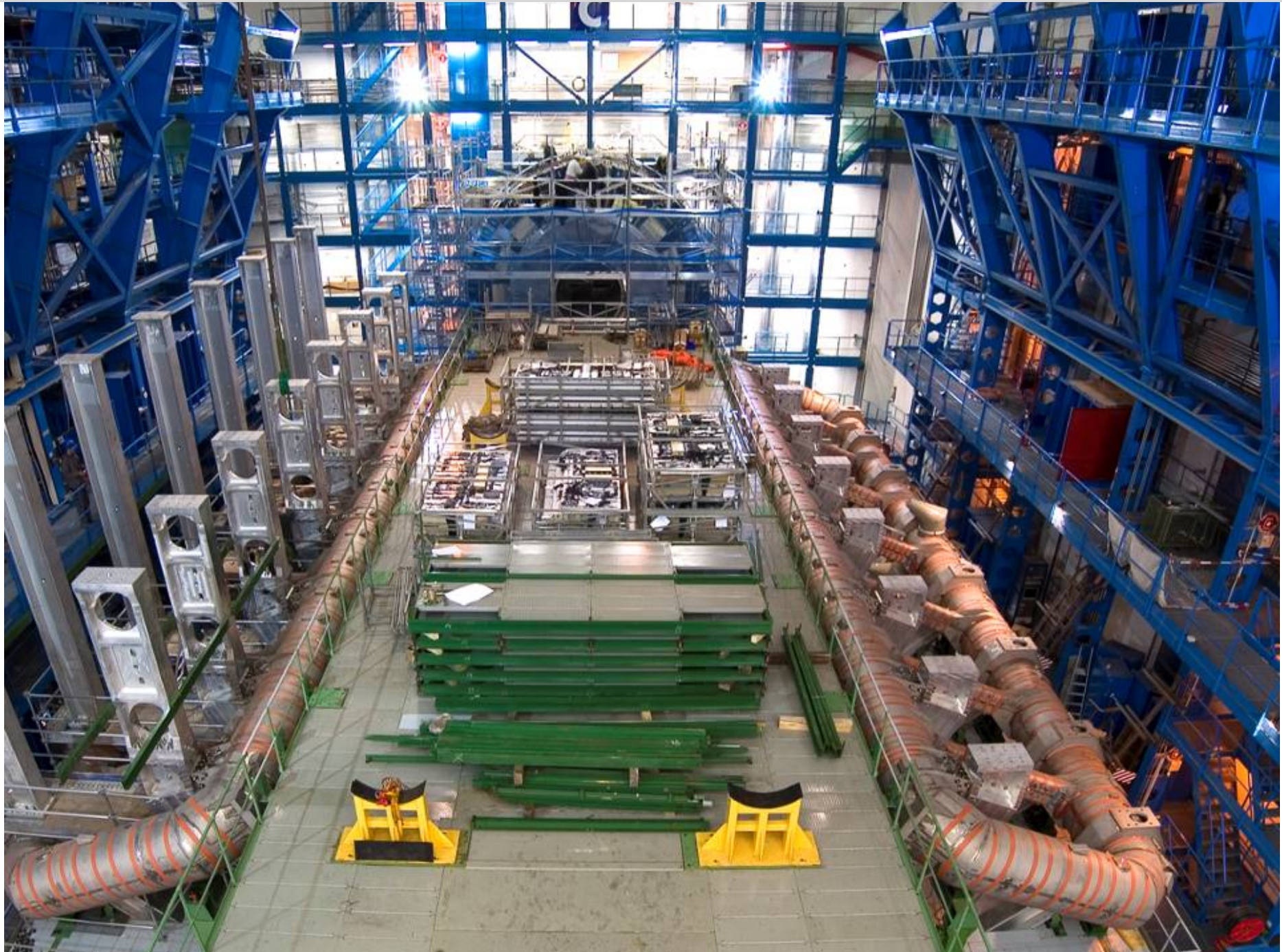
Der Bau des ATLAS Detektors



Der Bau des ATLAS Detektors



Der Bau des ATLAS Detektors



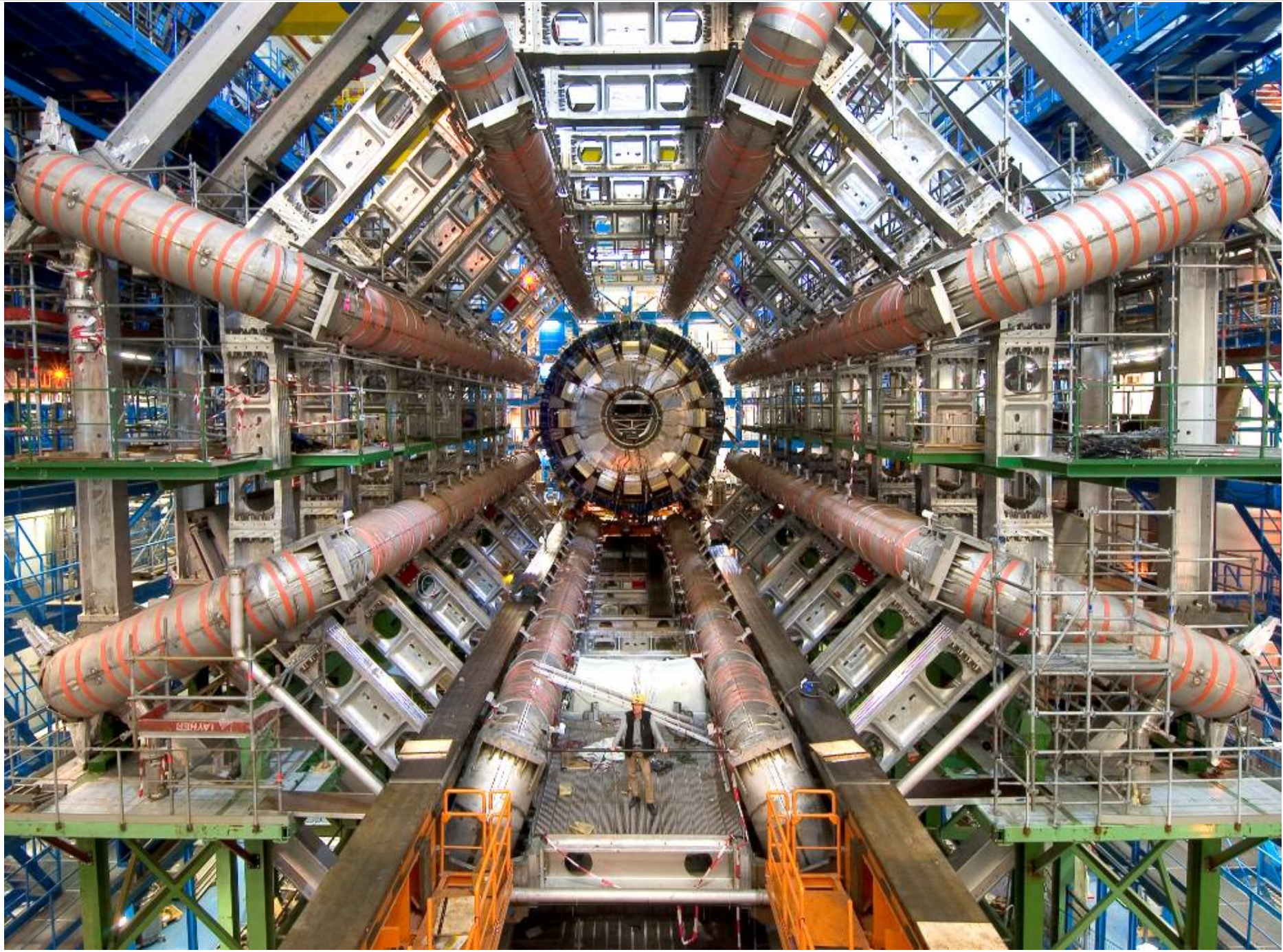
Der Bau des ATLAS Detektors



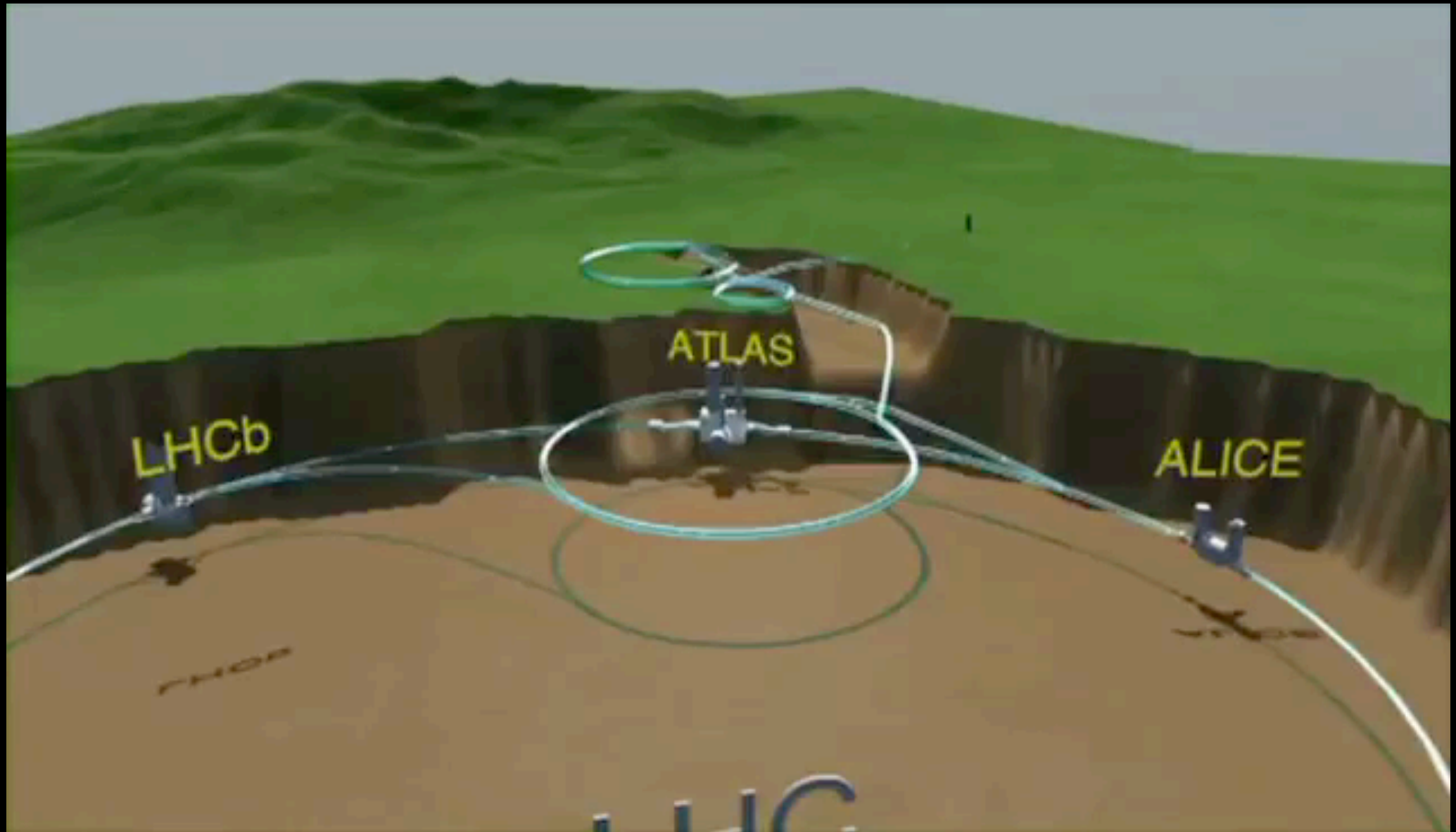
Der Bau des ATLAS Detektors



Der Bau des ATLAS Detektors

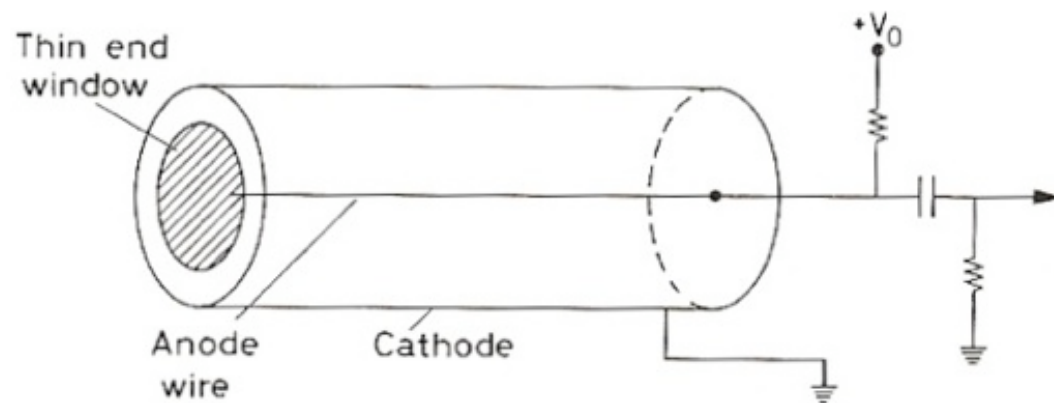


Collisions in the LHC



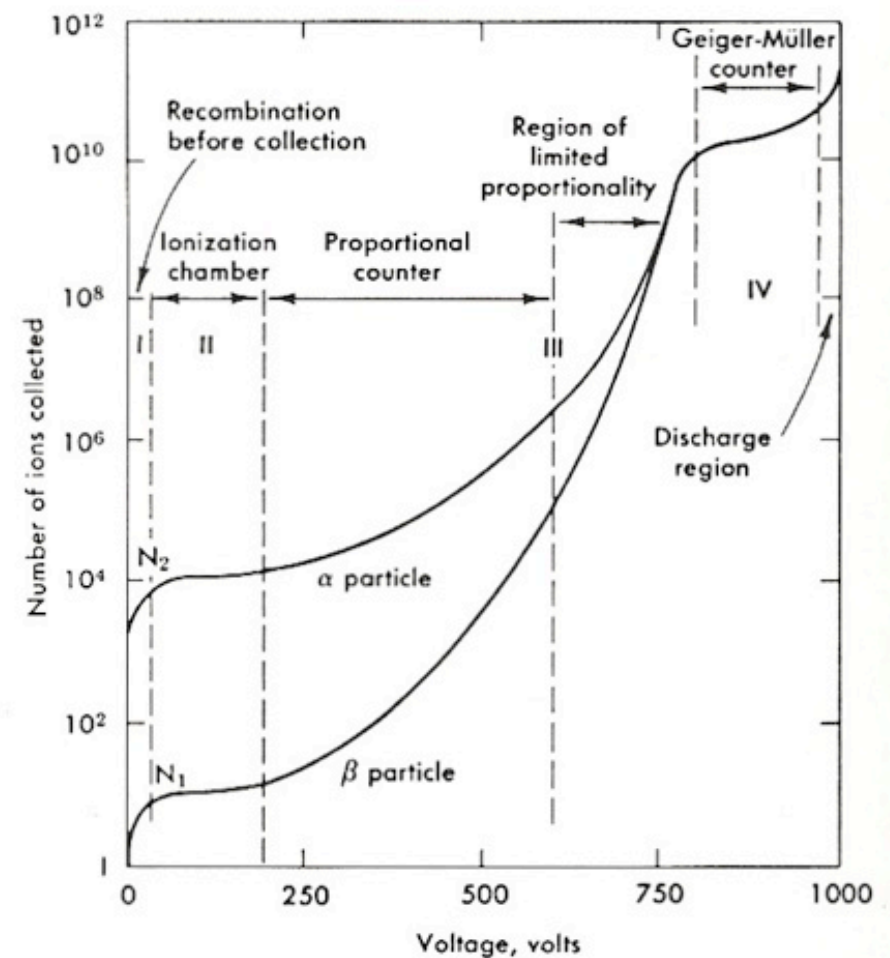
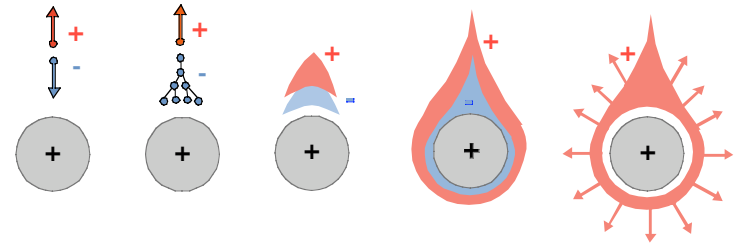
Eigene Arbeit am LHC: Der ATLAS Übergangsstrahlungsdetektor (TRT)

A classical one: the ionisation chamber



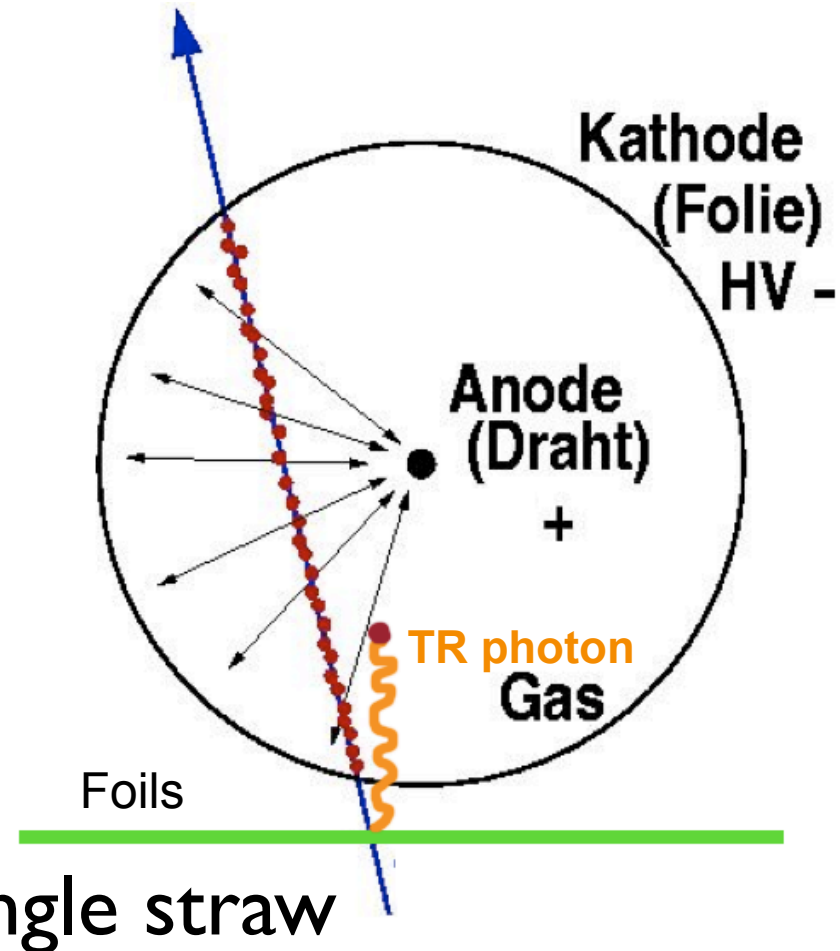
- Passage of particles creates within the gas volume electron-ion pair
- Electrons are accelerated in a strong electric field → amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)

Signal



The ATLAS TRT

- Transition radiation $\rightarrow$ X-ray photon is emitted when charged particle traverses boundary of materials with different dielectrical properties
- Depends strongly on the relativistic factor of the particle which makes it usable for particle identification
- used at LHCb, ATLAS
- advantages: additional info to tracking:
 $\Rightarrow$ particle identification
 - not (too) expensive
 - robust (assembly & transport)
- ATLAS Transition Radiation Tracker
 - 35 track points
 - 350000 straws in total

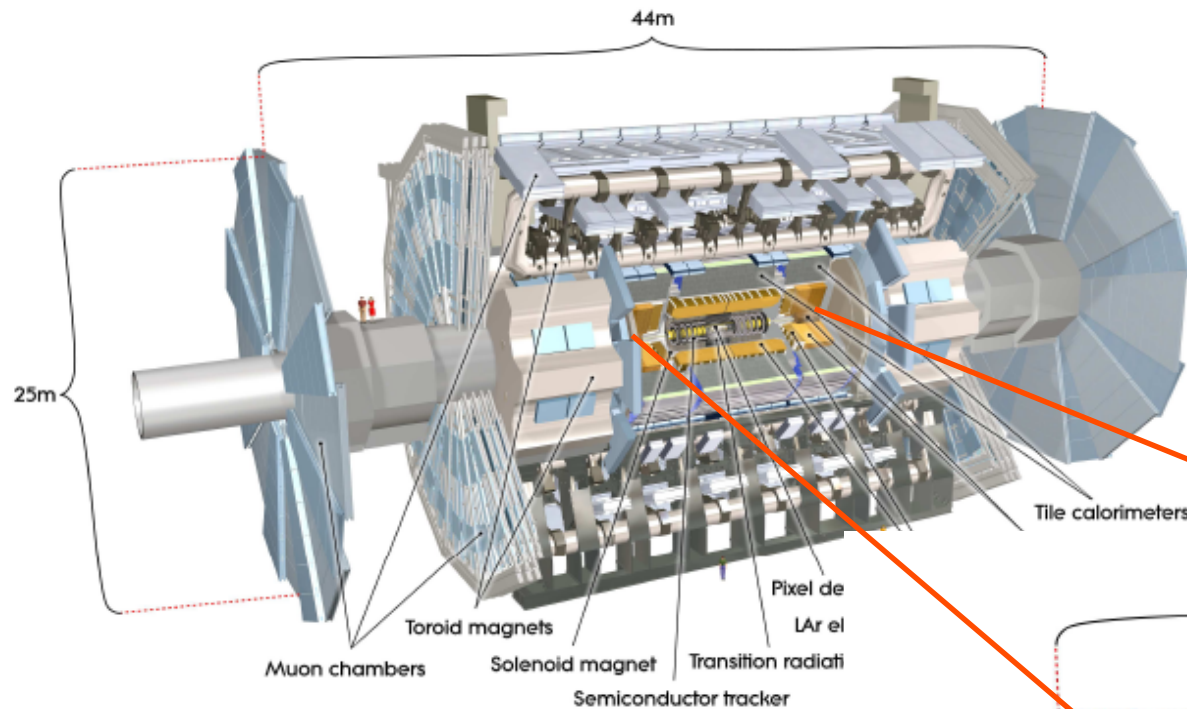


A single straw



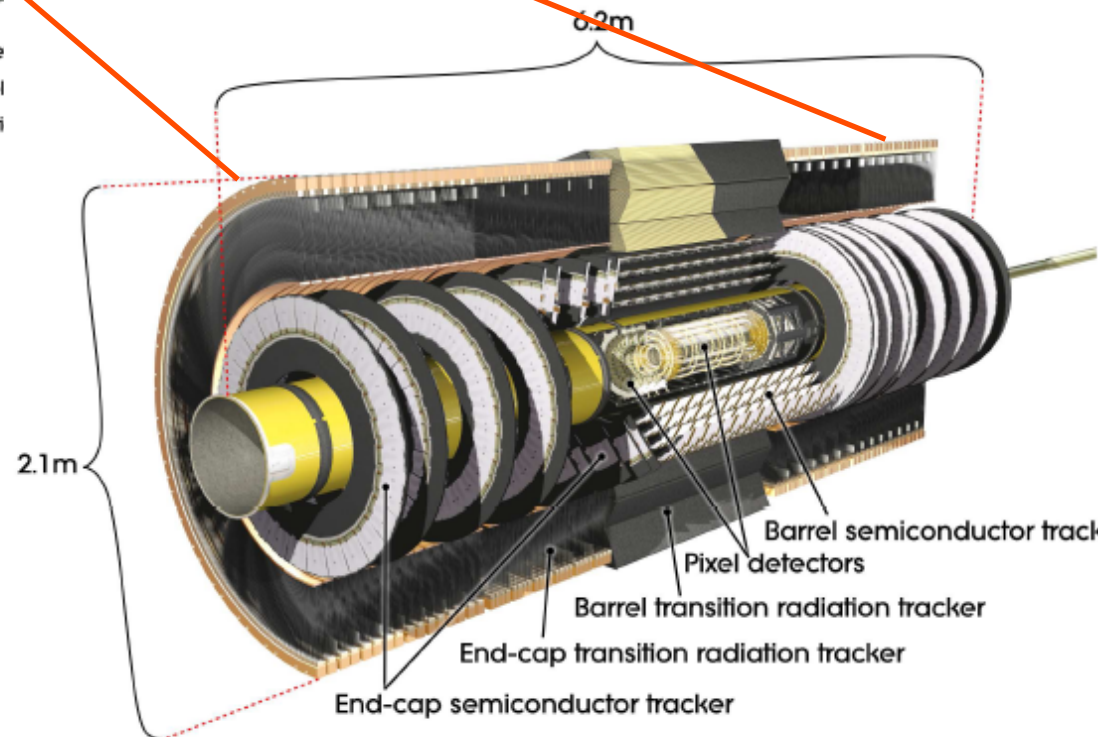
stiff straw, supported by **carbon fibre strips**, allows self supporting structures, thus reduced material inside the detector

Der ATLAS Übergangsstrahlungsdetektor (TRT)



Der TRT ist Teil des ATLAS Spurdetektors

- vermisst Spuren geladener Teilchen ($>0.5 \text{ GeV}$)
- Identifiziert Elektronen zwischen 1 und 150 GeV
- arbeitet in einem 2T Magnetfeld



The history of an LHC detector

Example: the **ATLAS TRT**

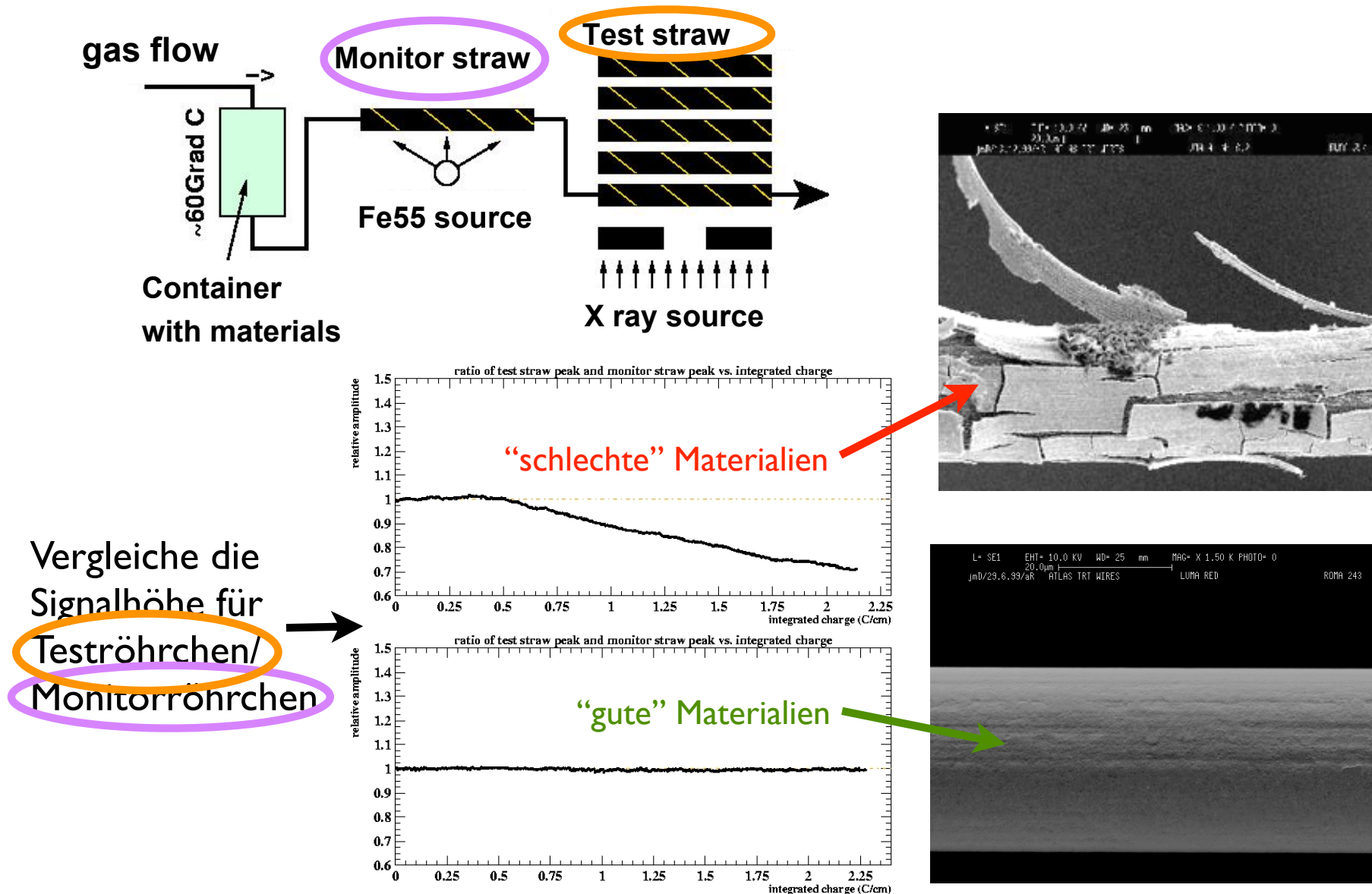
- 1989: R&D for the TRT begins (1990: RD6)
- 1994: LHC machine approved. First full-size TRT prototype completed (10'000 channels for end-cap wheel)
- 1996-1998: major Technical Design Reports for ATLAS construction approved, test beams
- 2000: assembly of barrel modules and end-cap wheels start. Front-end electronics specified and vendor chosen.
- 2002: wire-joint trouble
- 2003-2004: web trouble
- 2000-2007: many other troubles
- 2006: first cosmic tracks recorded
- 2006: installation of barrel ID in ATLAS
- 2007: installation of ID end-caps in ATLAS
- 2008: TRT routinely operated, first LHC beam seen (beam splashes)
- 2009: first proton collisions recorded
- 2010: first high energy proton collisions

Herausforderungen an einen LHC Detektor

Beispiel: der ATLAS Übergangsstrahlungsdetektor

- Sehr hohe Teilchendichten, 30 % aller Kanäle feuern;
- Sehr hohe Zählraten pro Sensor (Röhrchen), bis zu 20 MHz;
- Kurzer Abstand zwischen zwei LHC Paketen: 25 ns;
- Benötigt werden: sehr hohe Ortsauflösung, gute Spurerkennung → viele Spurpunkte;
- Detektoren müssen strahlenhart sein $\sim 10 \text{ MRad}$, 10^{14} n pro cm^2 und Jahr;
- Benötigt schnelles und chemisch nicht reaktives Gas, sonst schnelle Alterung!
- Sehr widerstandsfähige Materialien: ein Röhrchen in Betrieb (Hochspannung, Ionisationen) ist ein elektrochemischer Reaktor;
- Möglichst wenig Material (in Strahlungslängen)
- Sehr robuste und präzise mechanische Strukturen, $\sim 100 \mu\text{m}/\text{few m} \approx \sim 10^{-5}$;
- Temperaturstabil.

Beispiel: Strahlungstests aller Materialien des TRT

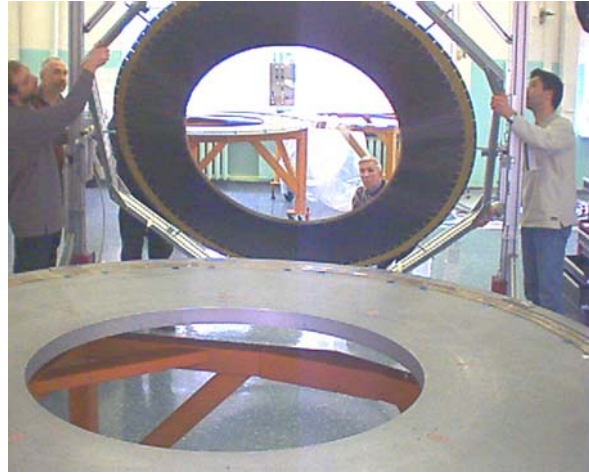


TRT end cap wheel production

- basic element: wheel with 4 straw planes



Installation of straws
(tests leak tightness)



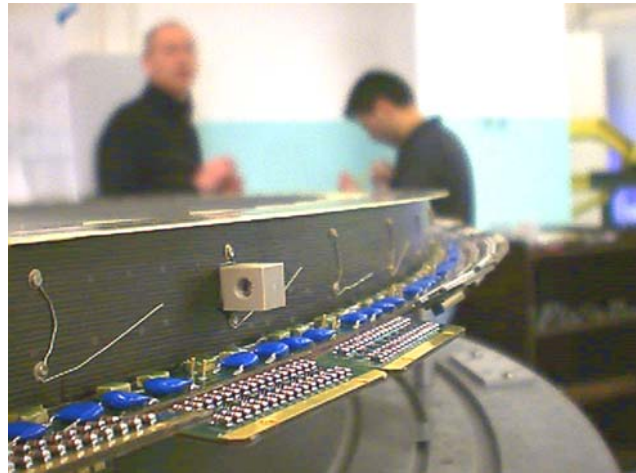
Transfer of wheel...



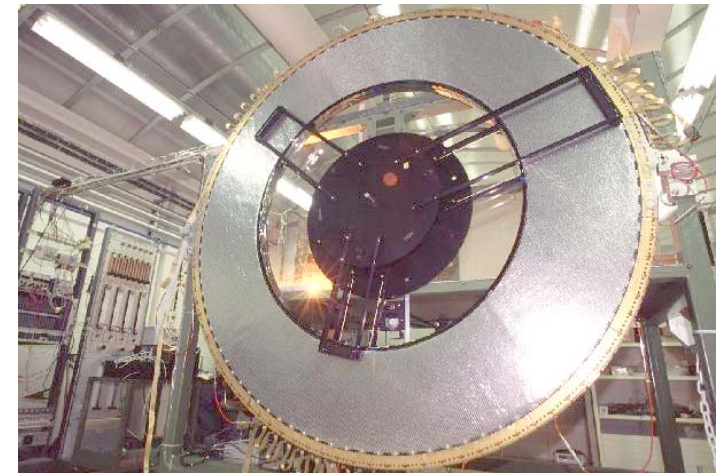
...to string wires



Fixating and connecting wires
(tests wire tension & HV)



Sealing of wheel
(tests leak tightness & HV)



Final acceptance tests
(test wire centricity etc.)

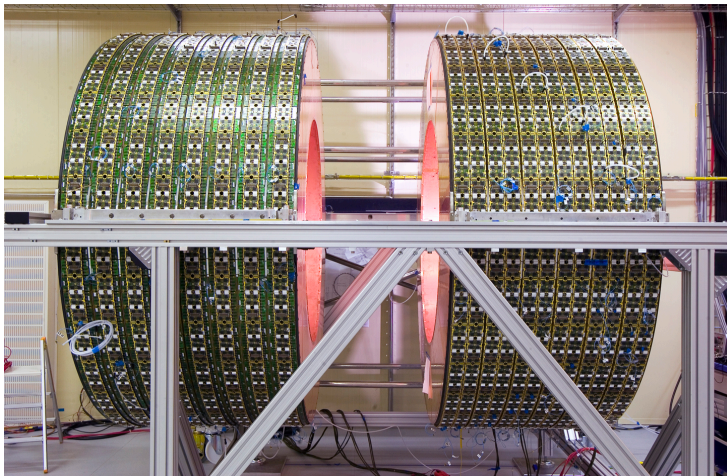
Mounting TRT end cap



After the wheels have been stacked...

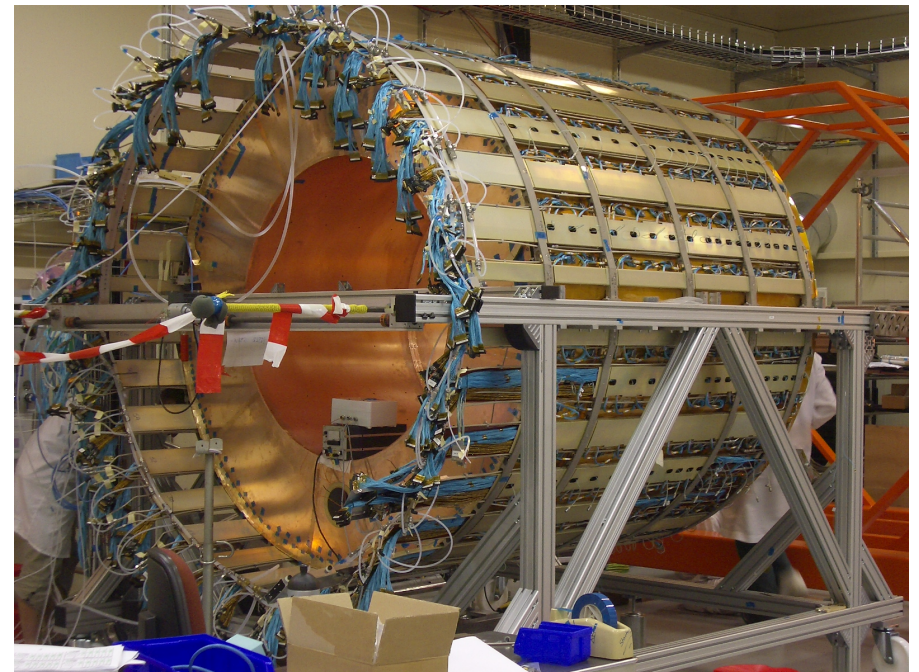


...the stack is rotated.



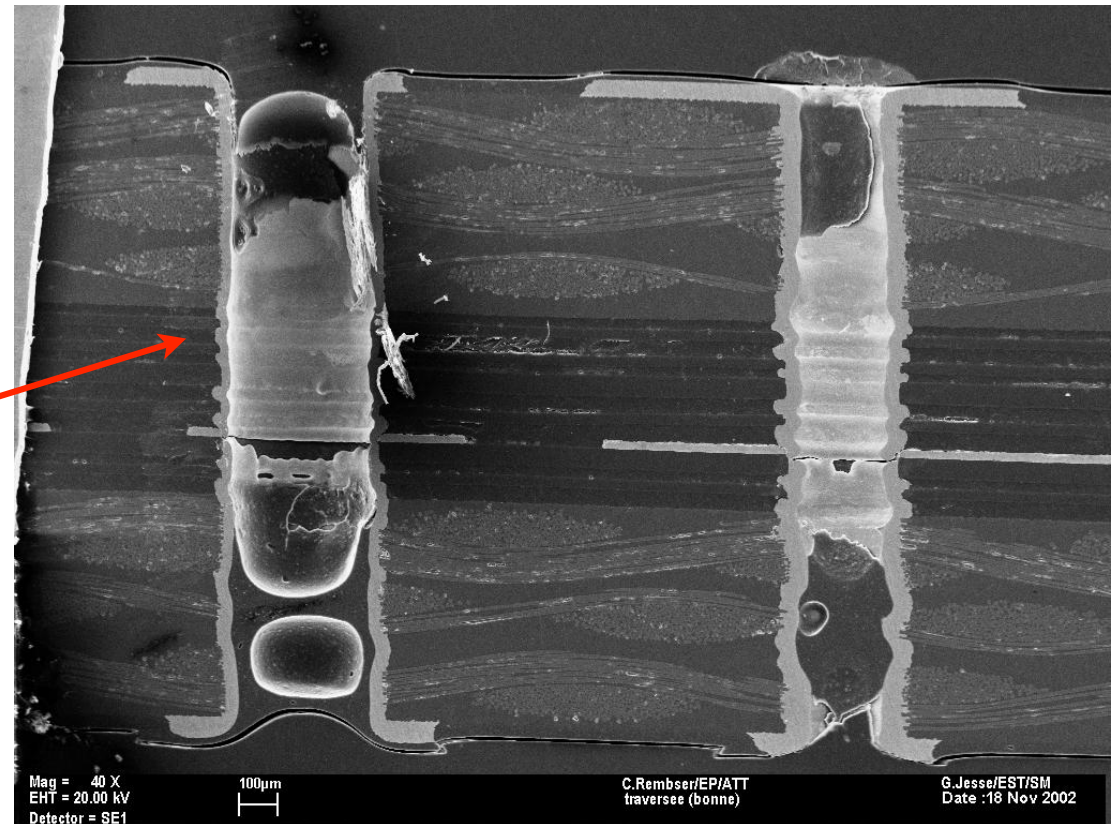
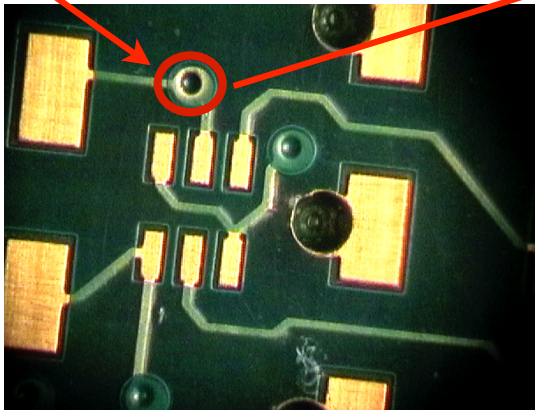
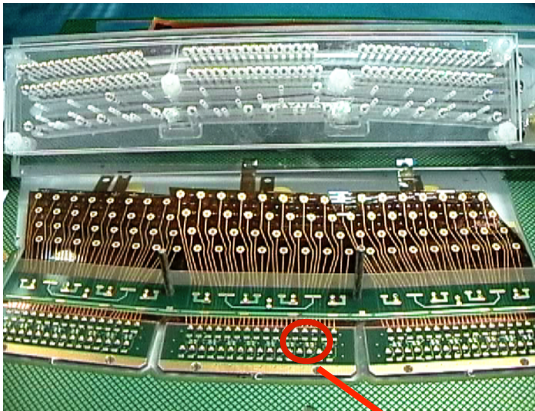
The two stacks of an end cap

The ready end cap, with all cables, pipes and supports (0.8% dead channels; ~50 man years of work)



Bad surprises (I)

- Wheel end cap electronics boards
(connecting straws to HV, read-out and main mechanical structure of end-caps)
- ➔ many problems during production and manufacturing

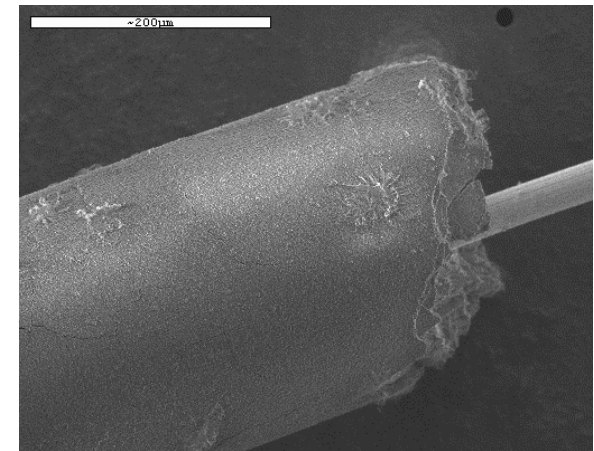


When building detectors

- ensure excellent quality control!!!
- ensure good contact to production companies!!!

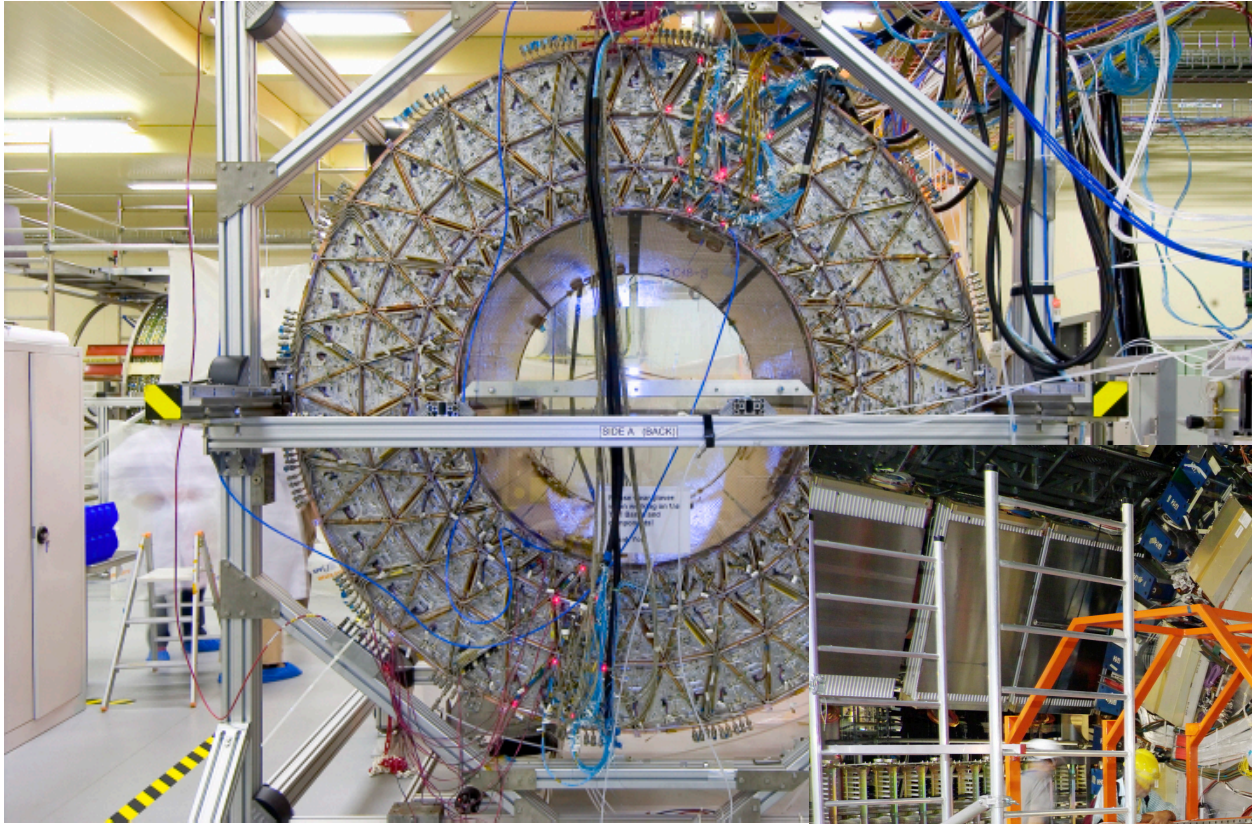
Bad surprises (2)

- Original TRT gas mixture (70% Xe, 20% **CF₄**, 10% CO₂) was destroying the detector (2002)
 - ➔ glass wire joints of barrel TRT “melting” with radiation 0.3-04 C/cm, less than 1 year nominal LHC operation
 - ➔ Reason: hydrofluoric acid HF



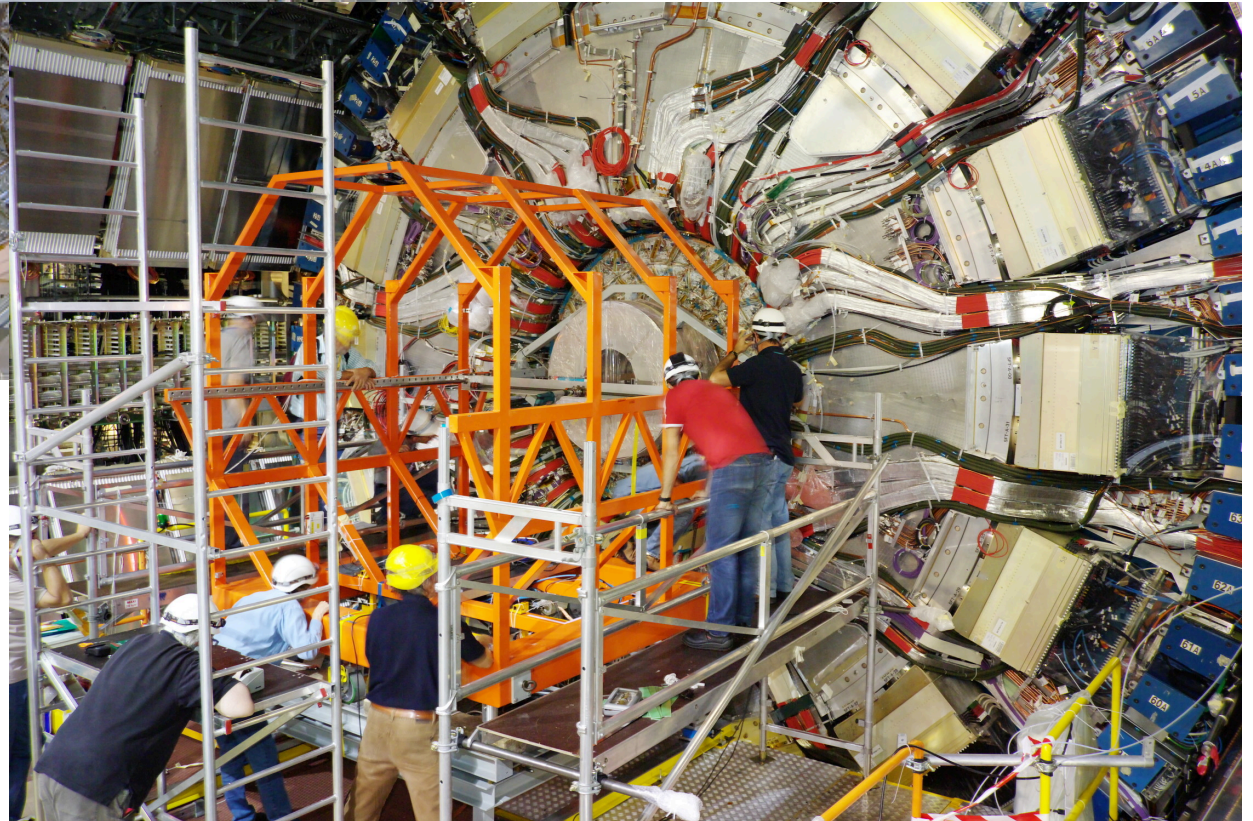
- Within one year, a new mixture was developed 70% Xe, 27% CO₂, 3% O₂
 - ➔ O₂ very unusual, strong quencher (“eats” electrons)
 - ➔ only works for TRT as straws have small diameter (lucky!)

But we managed...



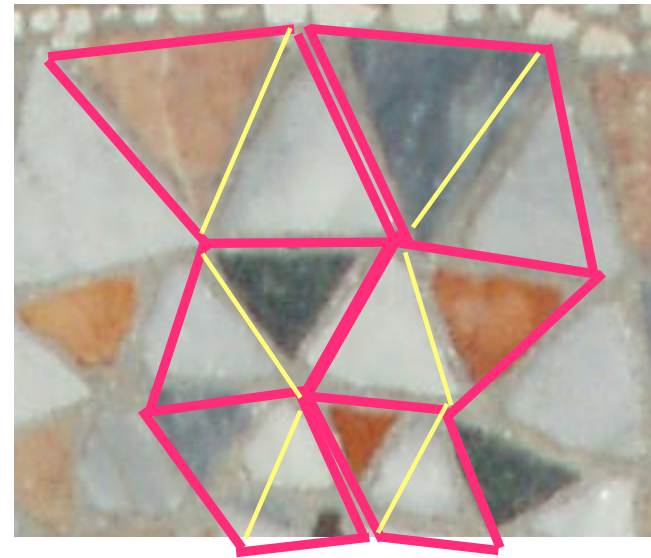
The TRT barrel in the assembly site

Installation into
ATLAS



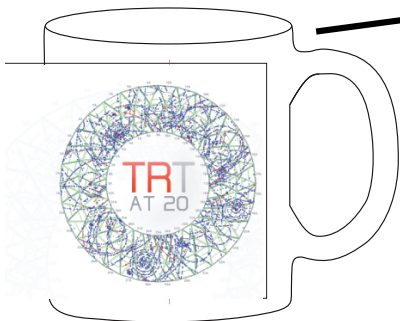
Inspired by a historical design (?)

- ATLAS - a 12th century mosaic in the Otranto cathedral in Italy



“Original” design has foreseen 4 layers.

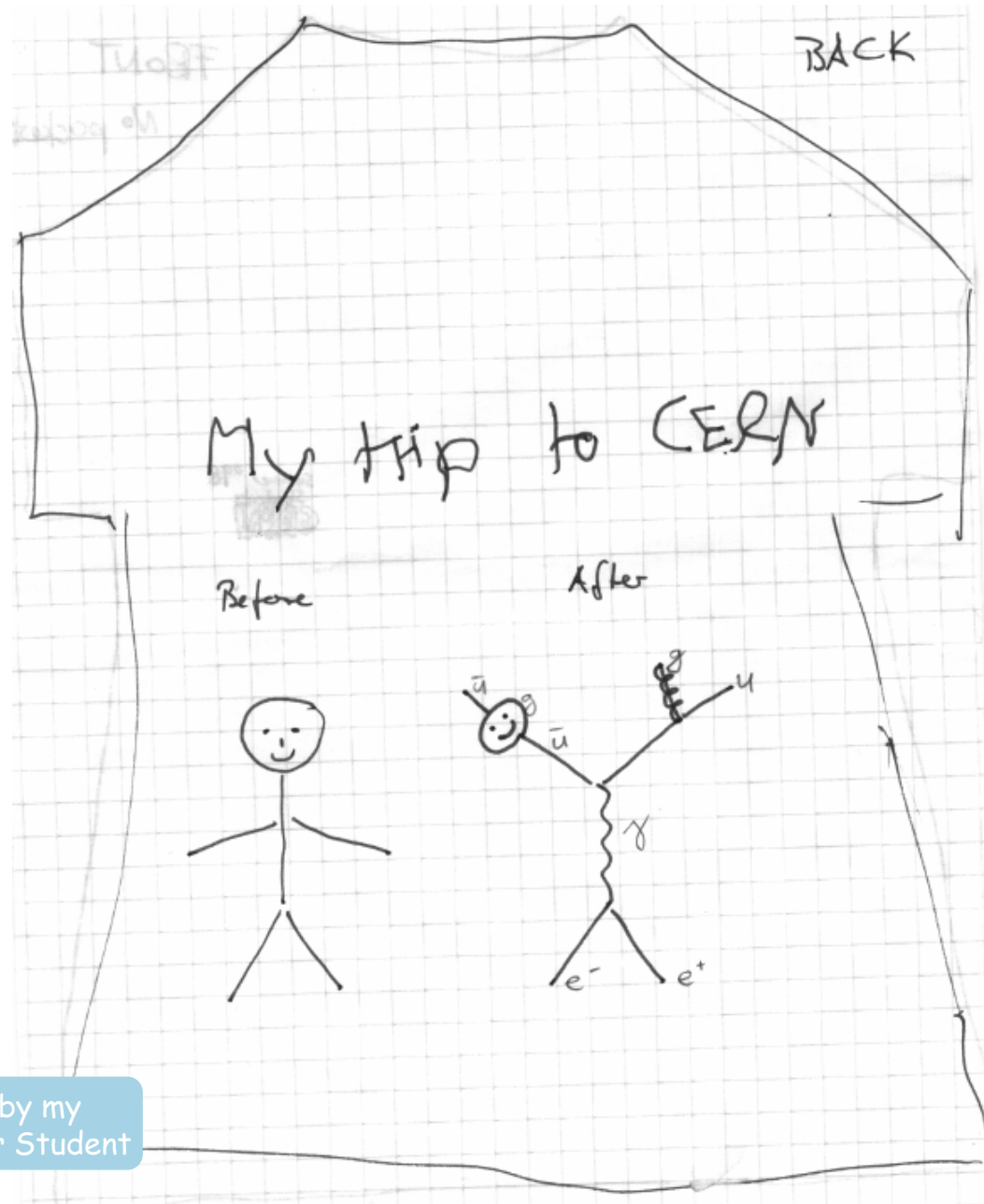
Ein “Fan” des ATLAS TRTs



Die TRT Kaffeetasse

Anstatt einer Zusammenfassung

Ein Besuch am CERN lohnt sich!



Designed by my
1998 Summer Student

Eine Möglichkeit: ein CERN-Projekt für 2014

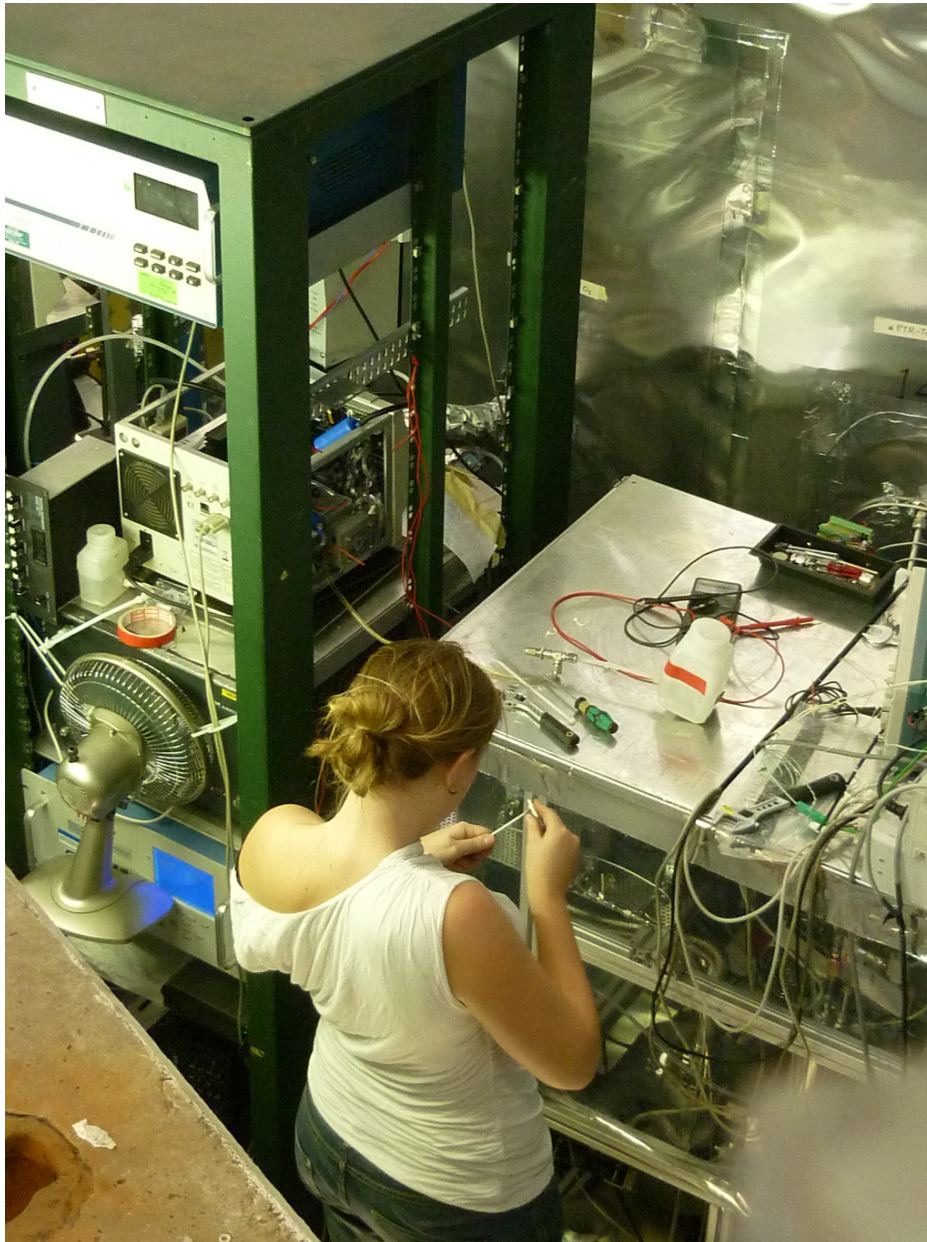


Photo: at a CERN PS beam line

The best way of learning
is to involve experience

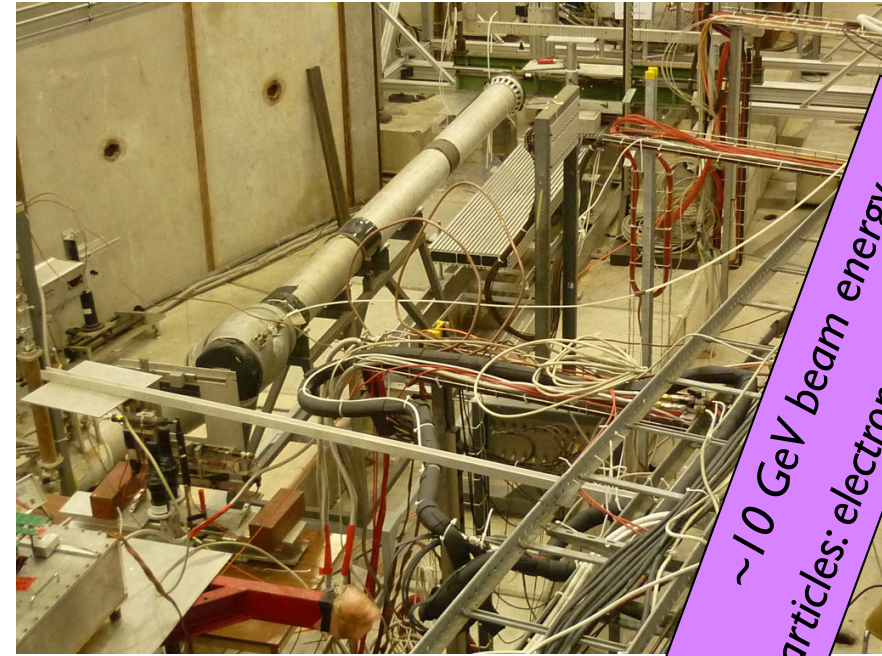
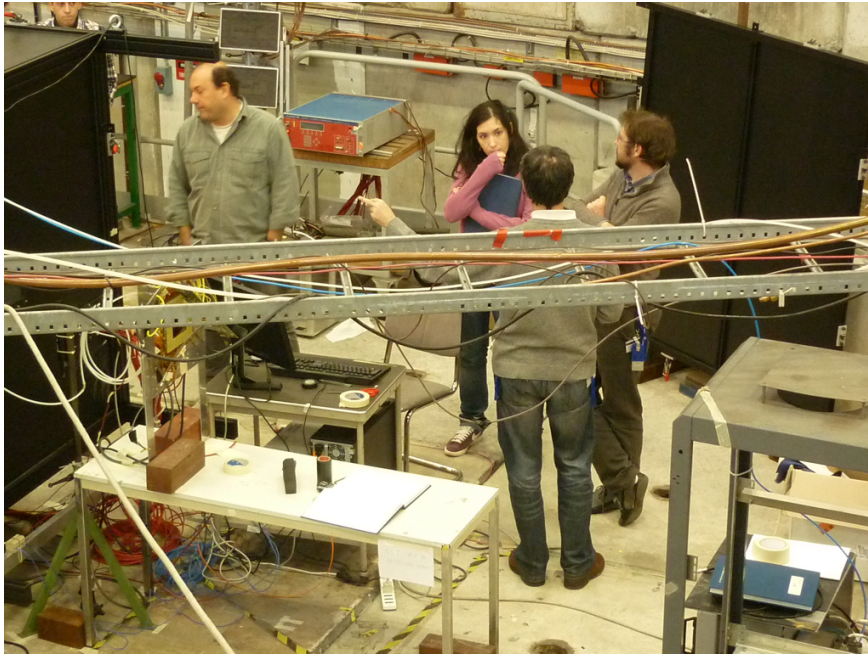
Eine Beamline für Schüler!
Es sollte bald losgehen!

Idea

- Worldwide competition among schools for beam time at CERN
 - ➔ class to phrase scientific question, to work out / design / build an experiment which uses particle beams and to write / submit a proposal;
 - ➔ a committee selects best proposals;
 - ➔ selected proposals are presented in the public session of the PS and SPS Experiments Committee (SPSC);
 - ➔ SPSC decides which experiment wins one week of beam time at a CERN accelerator;
 - ➔ class comes to CERN to do their experiment;
 - ➔ class writes up results (if possible results are published).

*As close as possible
to real science life*

Beam lines @ PS East Area



*~10 GeV beam energy,
particles: electrons, muons, pions*



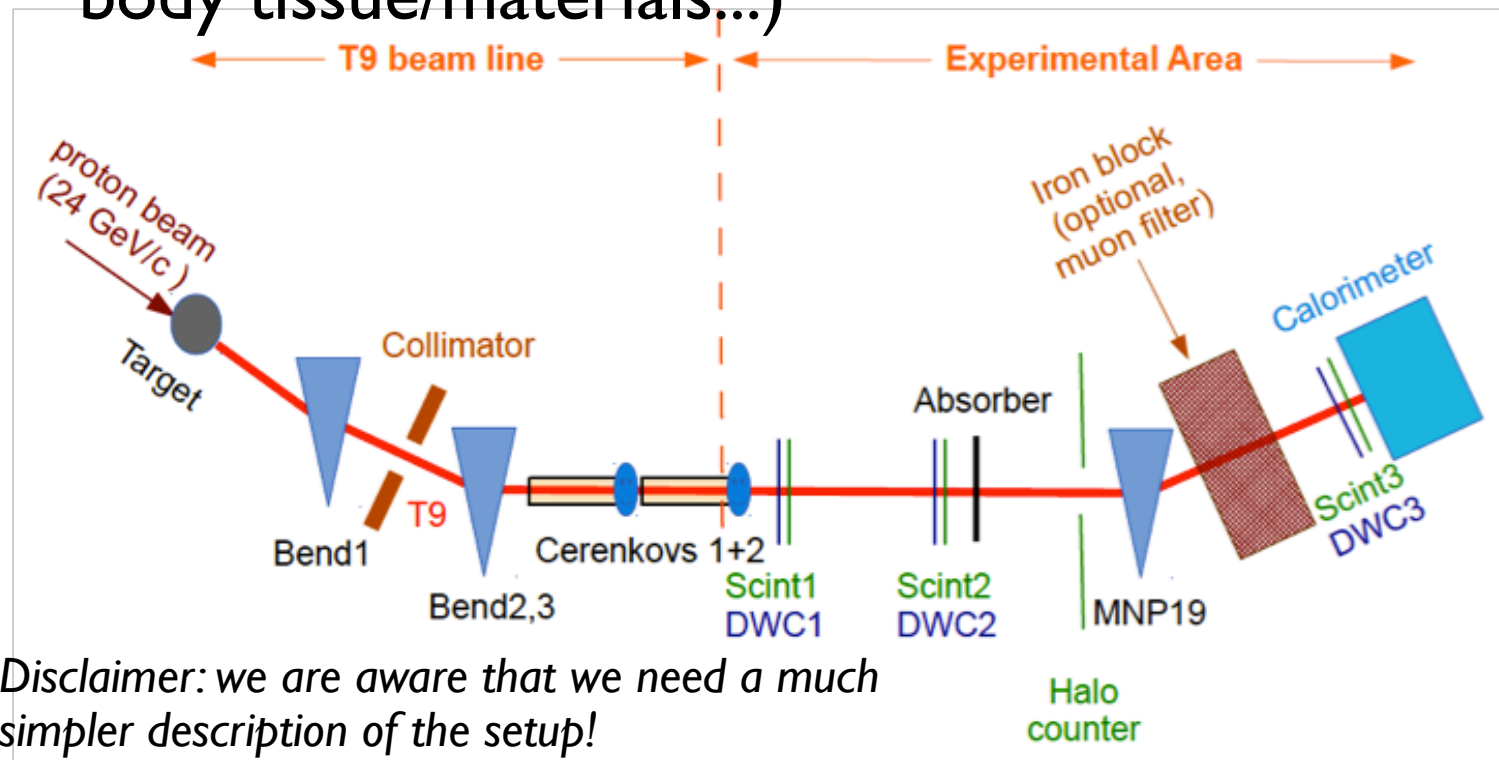
Photos: the T9 CERN beam line

PS East Area

- typical CERN beam line;
- easy access (and close to Restaurant I);
- excellent experimental conditions and reliable performance;
- ...

An example experiment

- Experiment to determine particle composition of the beam before and after an absorber (e.g. to study impact of particles on body tissue/materials...)



More ideas and examples to inspire the pupils are very welcome!

- Slight changes of the setup allow many other experiments.
- Example experiment should be used to explain available beam line, detectors and instrumentation.

Viel Spass!
Und herzlichen Dank für Ihre
Aufmerksamkeit.