



**CERN**

European Organization for Nuclear Research  
Organisation Européenne pour la Recherche Nucléaire

# Higgs-Jagd an der Weltmaschine

**Th. Naumann**  
Deutsches Elektronen-Synchrotron  
**DESY**

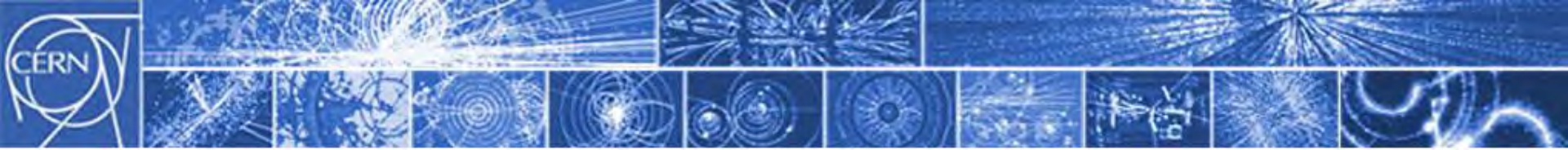


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# Das größte Teilchenphysik-Labor der Welt



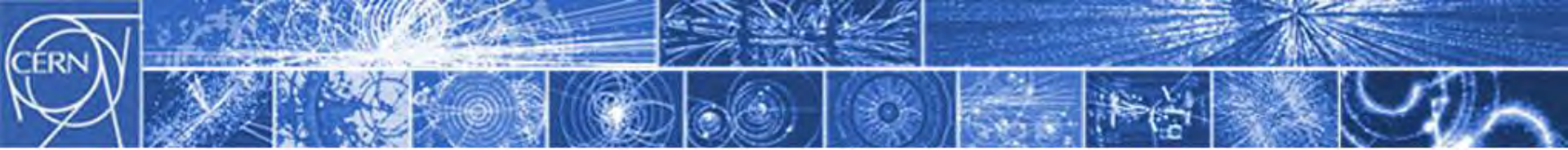


**Das größte Experiment der Menschheit**

**Large Hadron Collider**

**LHC**

**bei Genf**



**Die großen Fragen**

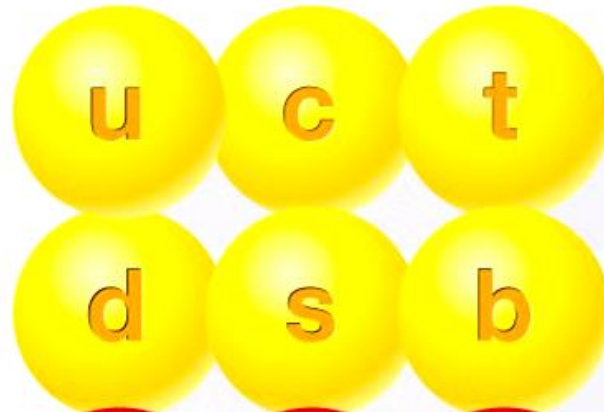
**Die Weltmaschine**

**Die Experimente**

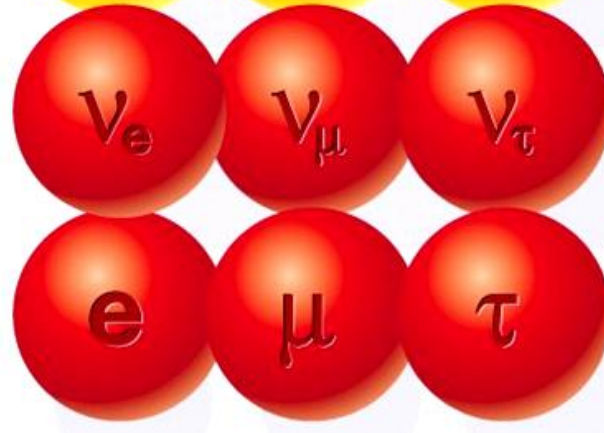
**Resultate: Higgs**

# Die Bausteine der Welt

**QUARKS**

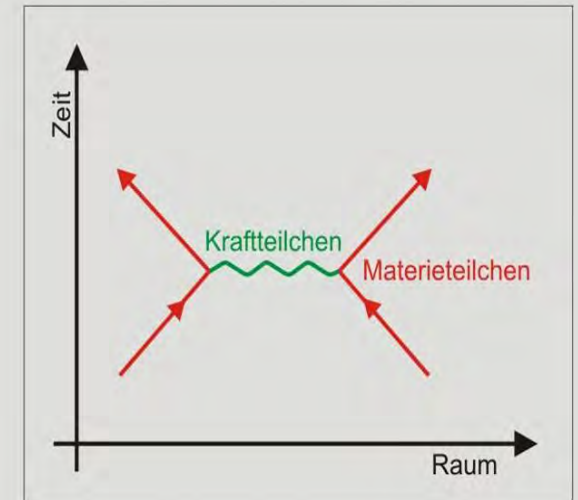
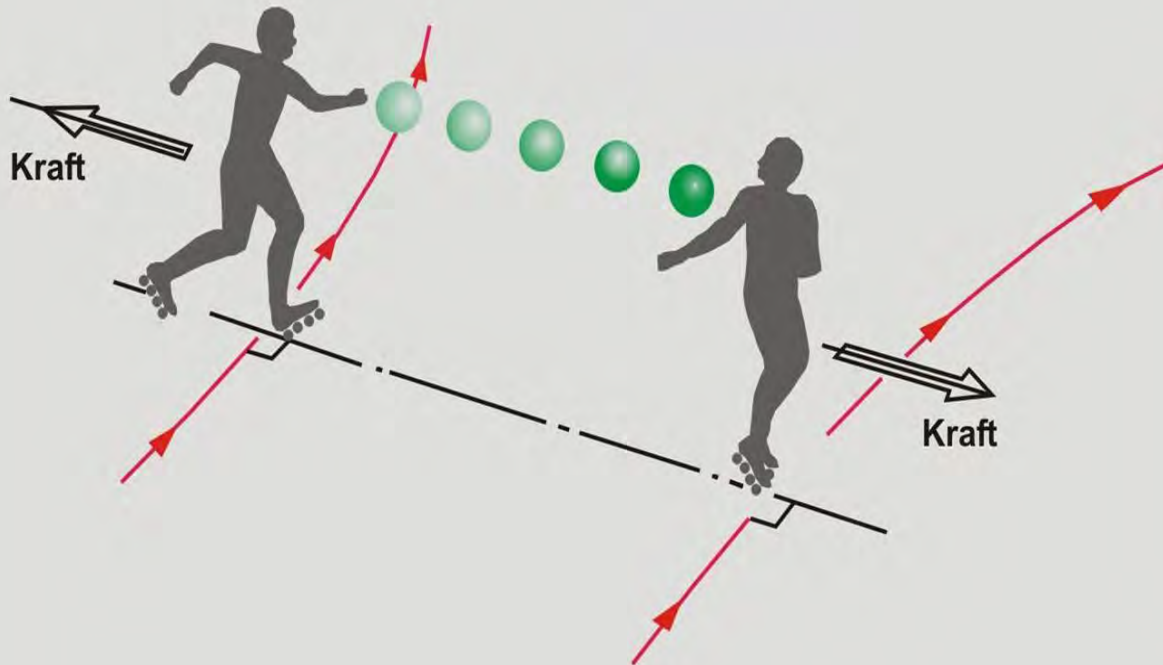


**LEPTONEN**



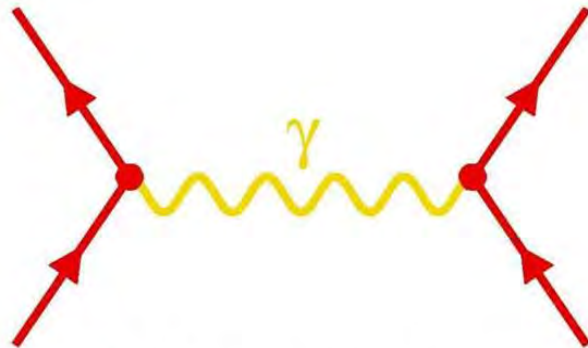
# Kräfte

werden vermittelt durch

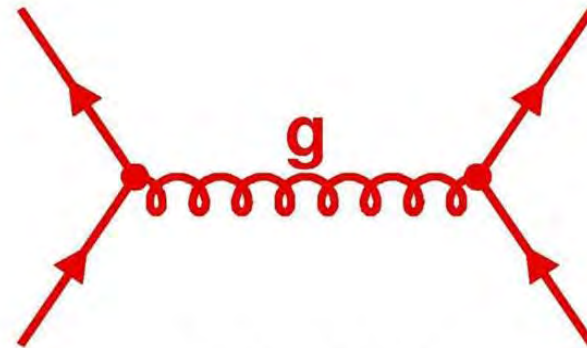


**Austausch von Teilchen**

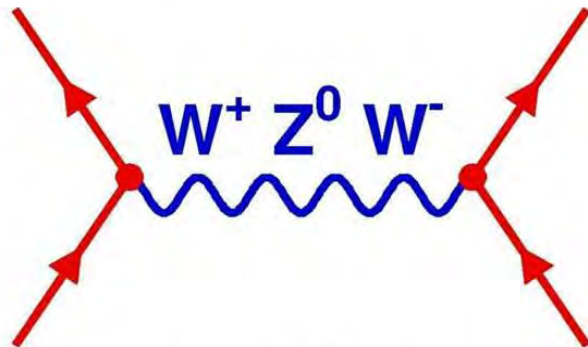
# Die vier Kräfte



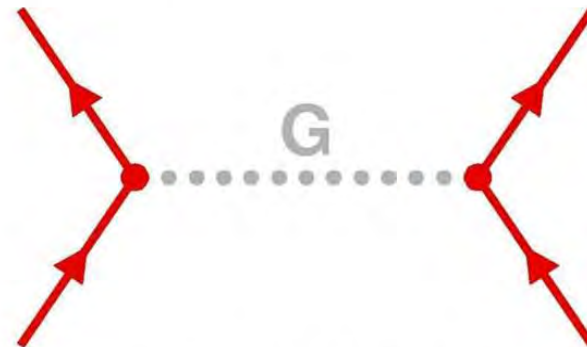
elektromagn. Kraft



starke Kraft



schwache Kraft

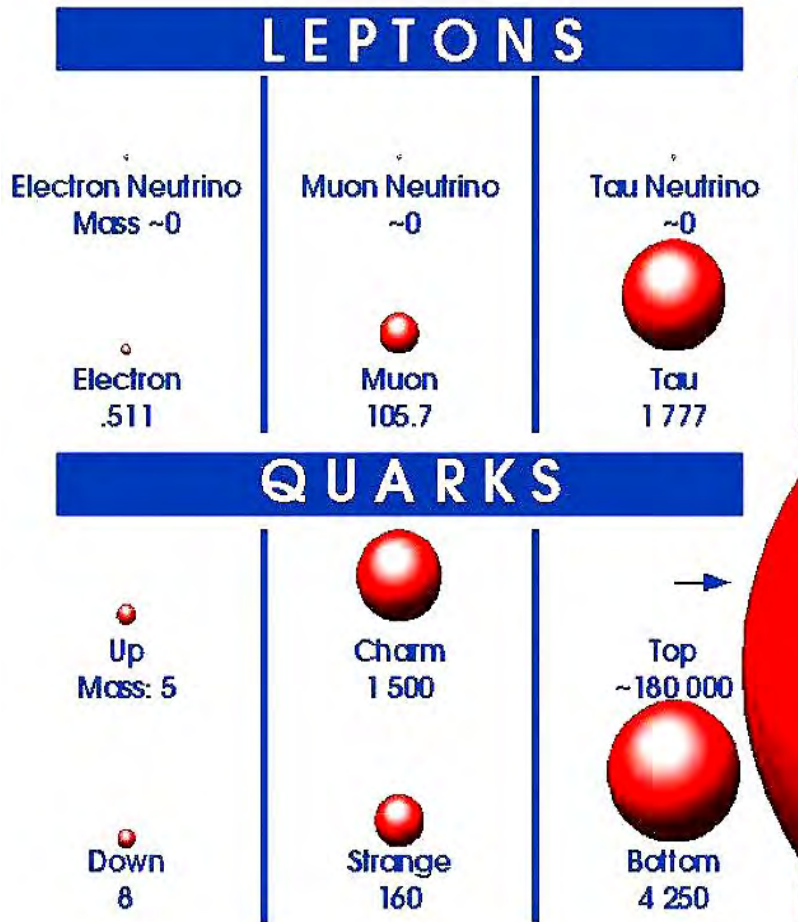


Gravitation

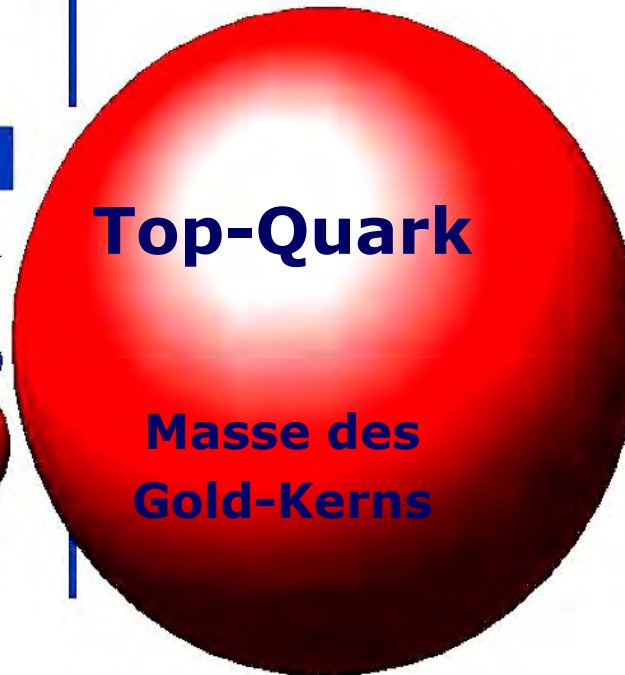
# Das Higgs- Teilchen



# Was ist Masse ?



**Was fixiert  
diese  
Massen?**

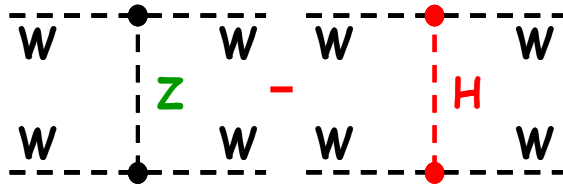


# Was ist Masse?



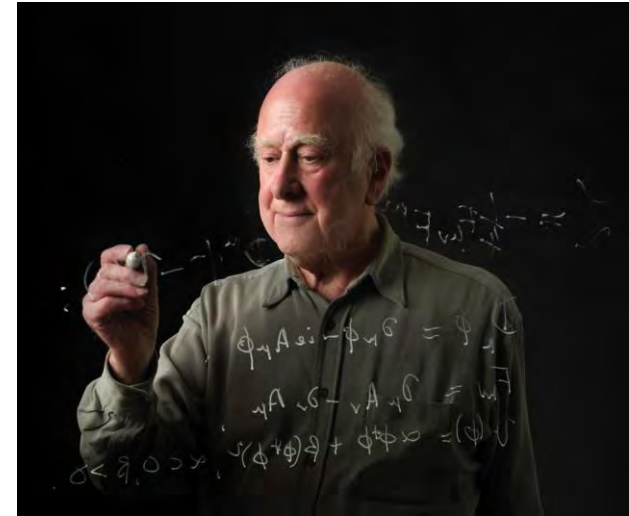
# Higgs-Mechanismus

- Theorie der elektromagnetischen, schwachen + starken Kraft ist perfekt.
- **Eichtheorie:** Freiheit, Potentiale umzueichen: **Elektromagnetismus**
- **Photon** + **Gluon** masselos - ok, aber: **W-Bosonen massiv** => **eichverletzend** => **WW-Streuung >100% !**
- **neues Higgs-Feld** kürzt eichverletzende Terme:



- **Higgs-Teilchen:** ermöglicht Masse
- Schluss-Stein der Theorie -  
Suche am LHC !**

- **koppelt** nicht universell, sondern  $\sim$  **Masse**



**Peter Higgs 1964**

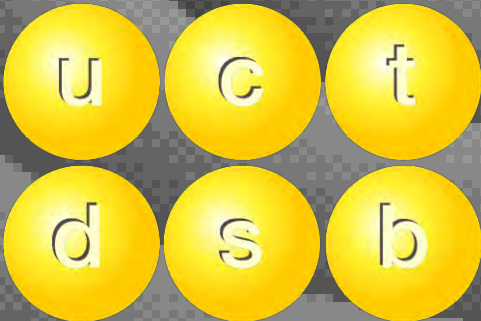


**Nobelpreis 2013  
mit J. Englert**

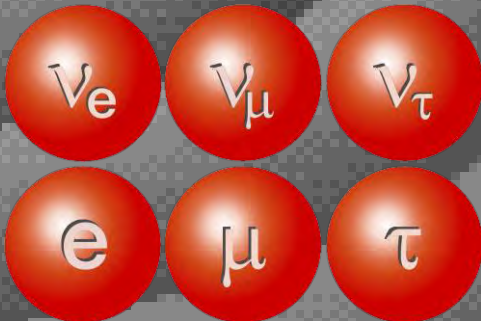
aber auch:

**Anderson, Nambu, Goldstone  
Brout, Kibble, Hagen, Guralnik  
Weinberg, t'Hooft, Veltman**

# Schwache Bosonen



Quarks



Leptonen

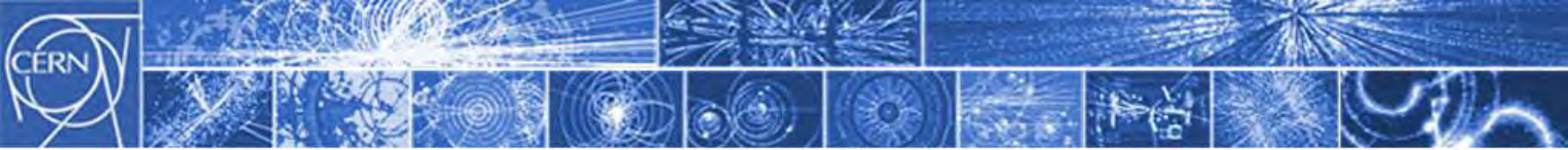


Nobel laureates Peter Higgs (right) and François Englert at CERN in July 2012.

NOBEL PRIZE

# Higgs theorists amass physics prize

*François Englert and Peter Higgs rewarded with Nobel  
50 years after hunt for boson began.*

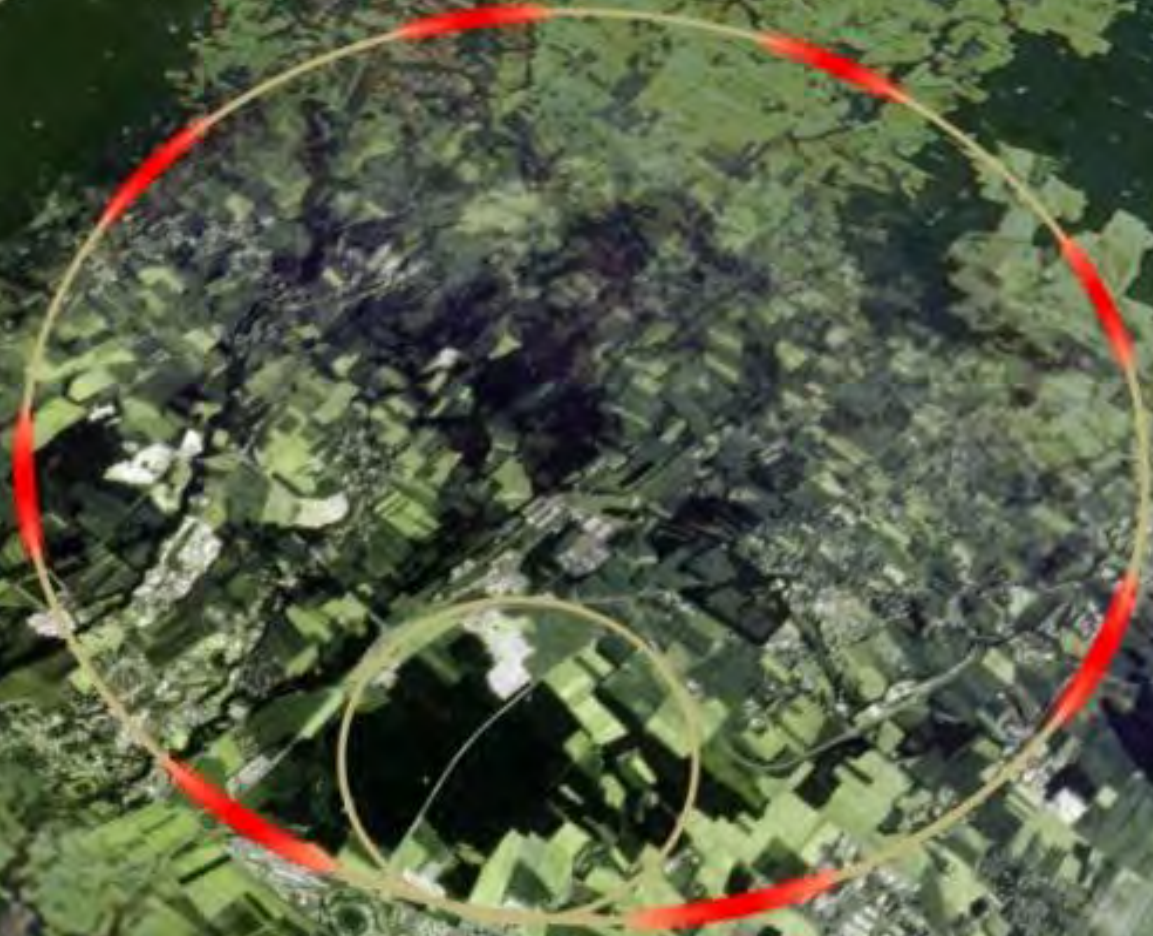


**Das größte Experiment der Menschheit**

**Large Hadron Collider**

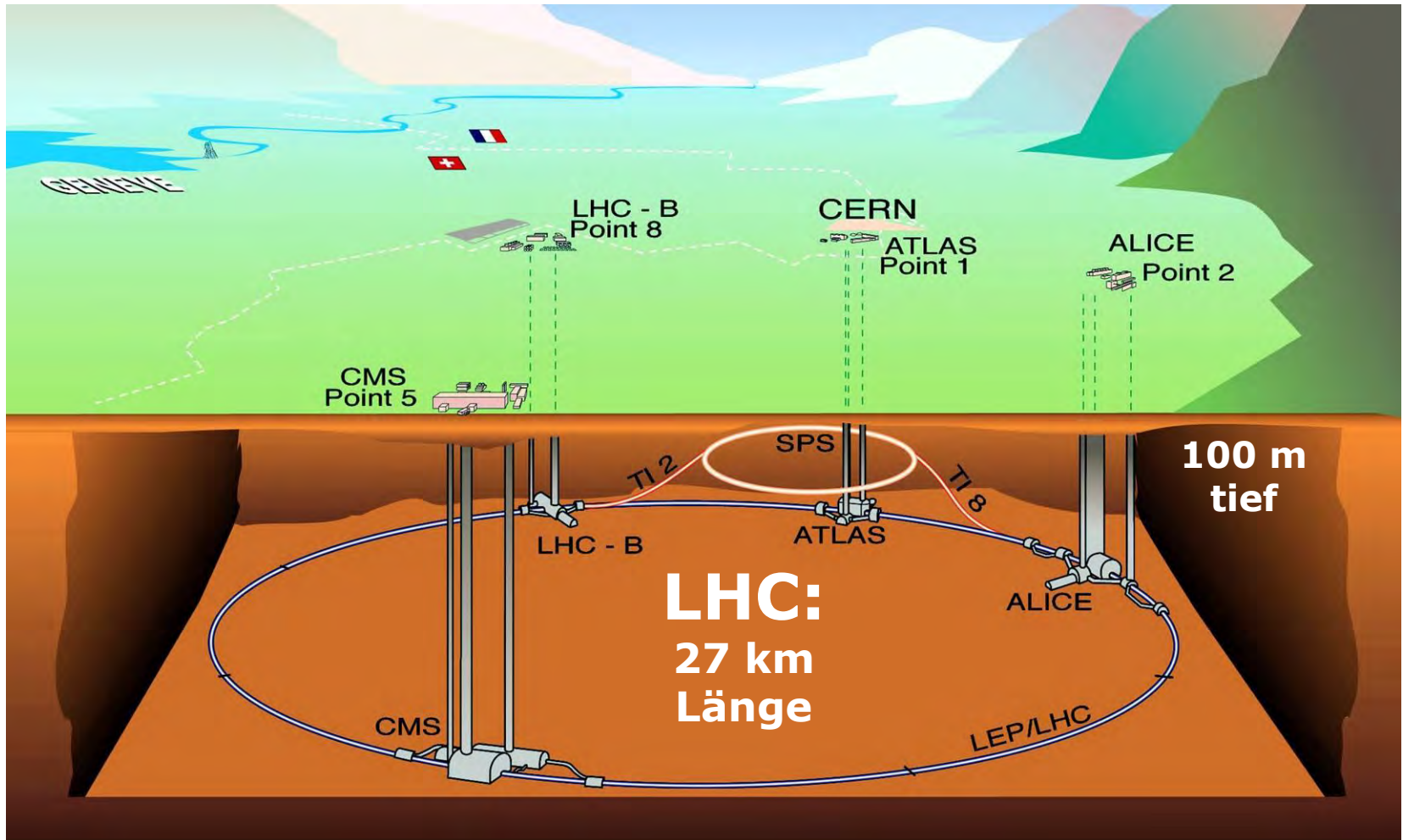
**LHC**





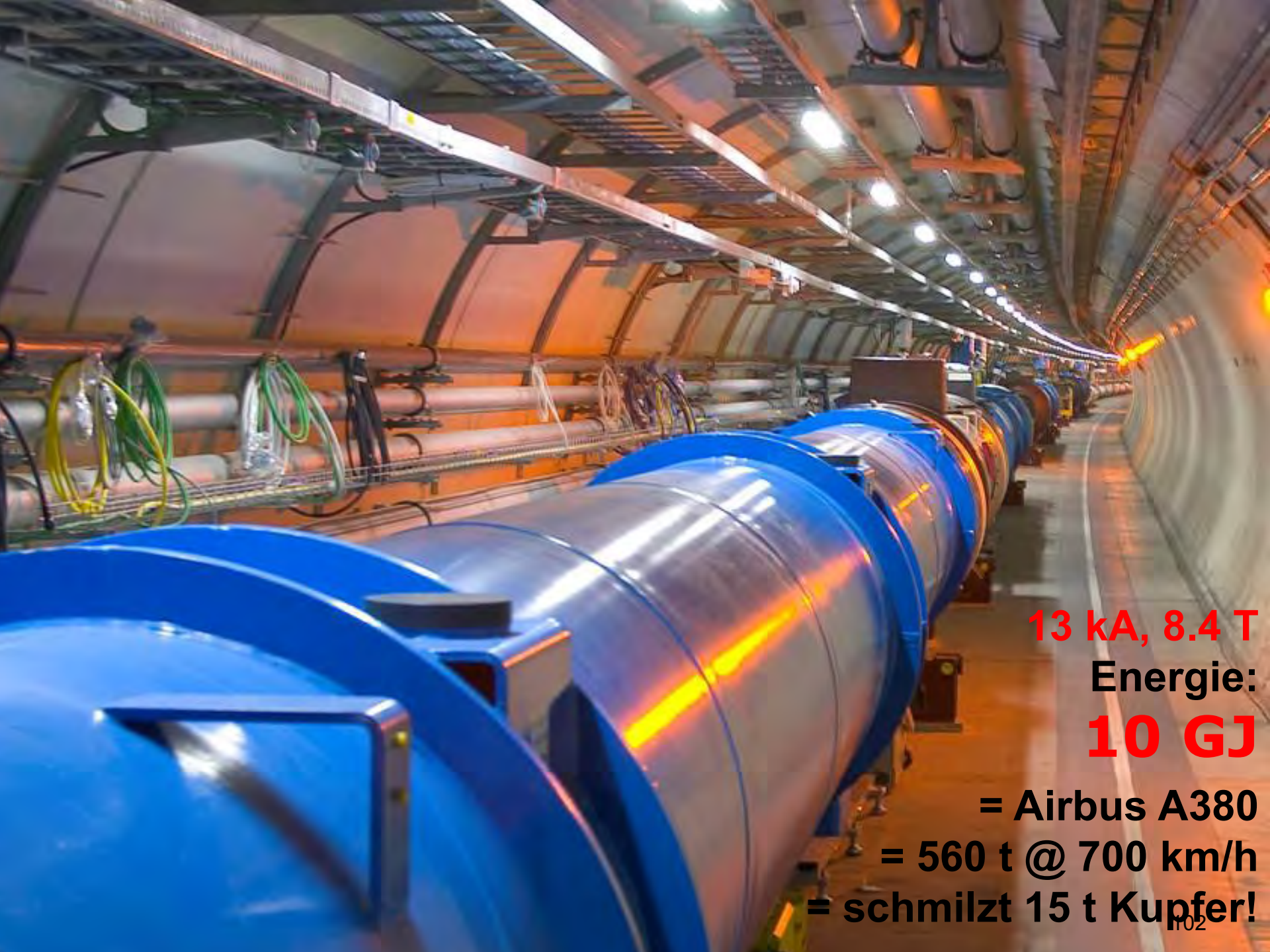


**Protonen kreisen im LHC gegenläufig.**



**Sie werden auf 7 TeV beschleunigt und kollidieren in 4 Experimenten.**





**13 kA, 8.4 T**

**Energie:**

**10 GJ**

**= Airbus A380**

**= 560 t @ 700 km/h**

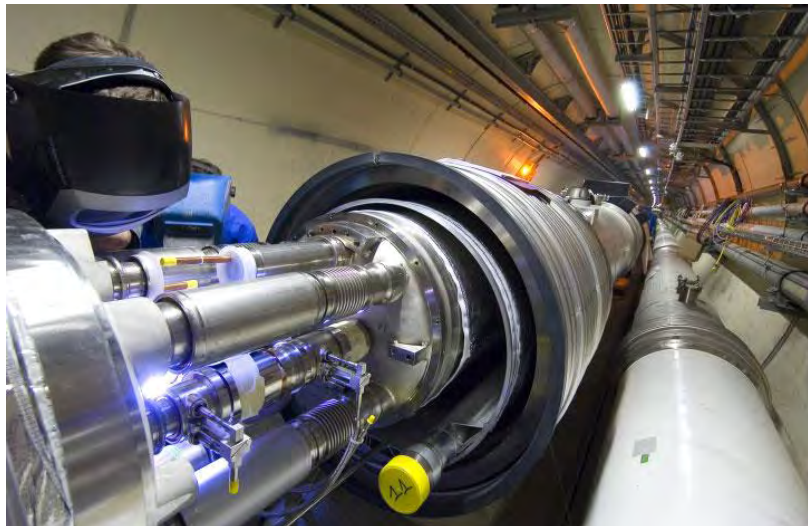
**= schmilzt 15 t Kupfer!**

## Die schnellste Rennbahn der Welt



**Einige tausend Milliarden Protonen umrunden den 27 km langen Ring über 11 000 Mal je Sekunde.**

# Leerer und kälter als der Weltraum !



Der **Druck** in den Strahlrohren von  $10^{-10}$  Torr ist ca. 10 Mal niedriger als auf dem Mond.

Mit einer **Temperatur** von **1.9 K** ist der LHC kälter als der Weltraum mit 2.7 K.

Das Vakuum von  $9.000 \text{ m}^3$  hat das Volumen einer Kathedrale.

**10.000 t** Stickstoff und **135 t** Helium kühlen **37.000 t** Material.

> 1 LKW/h, 470 total

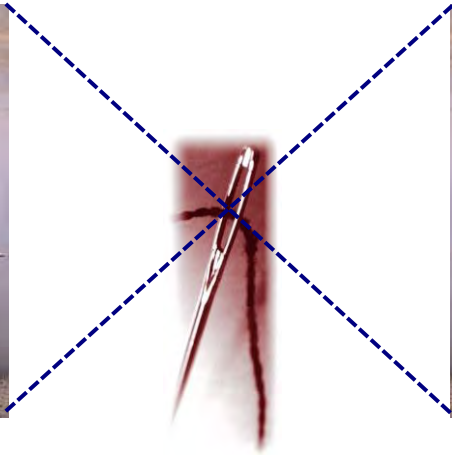
# LHC Strahl

**Gesamtenergie der Protonstrahlen: 2x350 MJ**

**240 Elefanten auf Kollisionskurs**



120 Elefanten mit 40 km/h



**Nadelöhr:**

**0.30 mm Durchmesser**

**Protonstrahl am Kollisionspunkt:**

**0.02 mm Durchmesser**



120 Elefanten mit 40 km/h

**Proton-Energie:**  
**Mücke im Flug**  
**1  $\mu$ J**



# Experimente

**ATLAS**

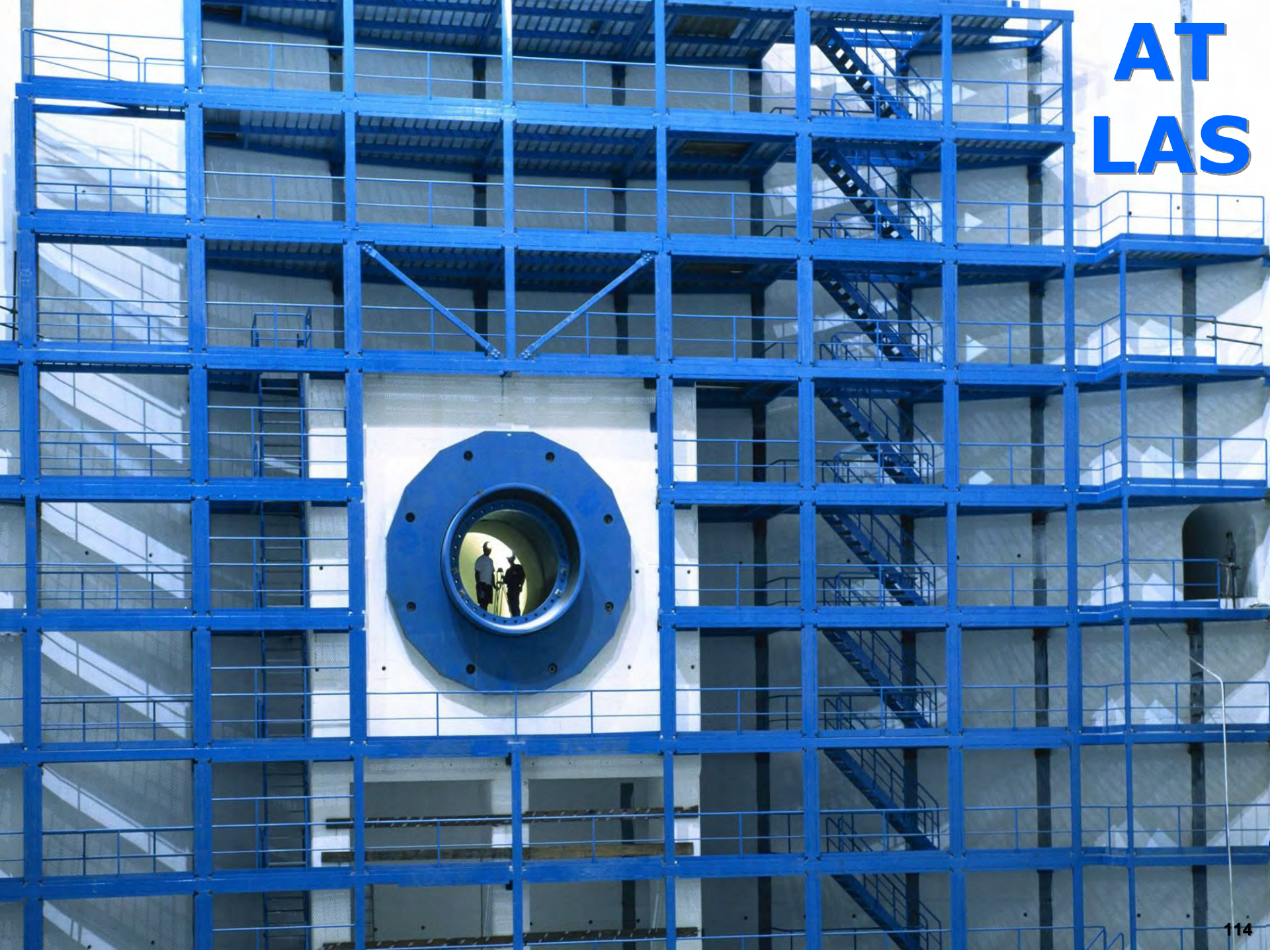
**> 3.000 Physiker**

**177 Institutionen**

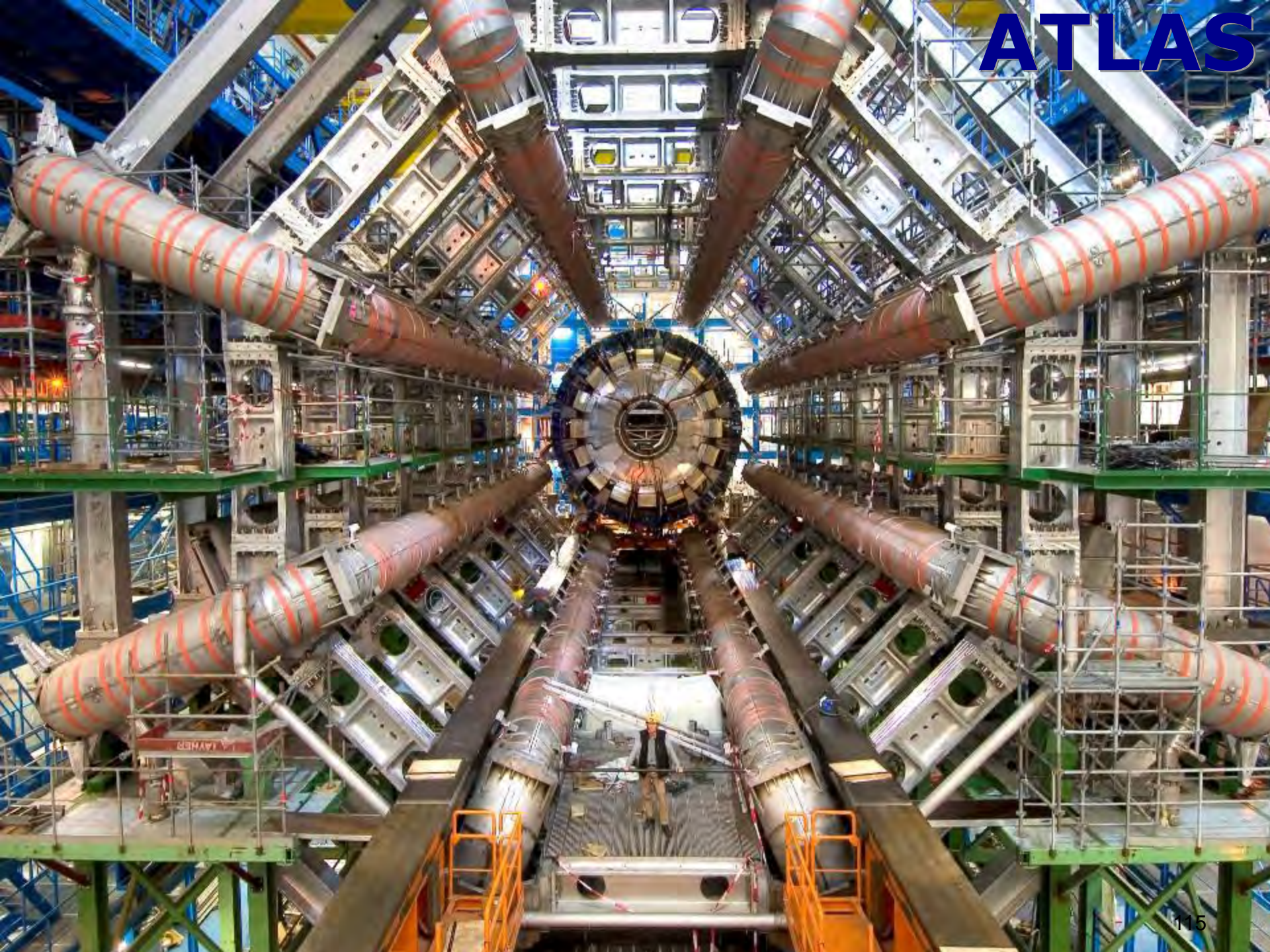
**38 Staaten**



# AT LAS



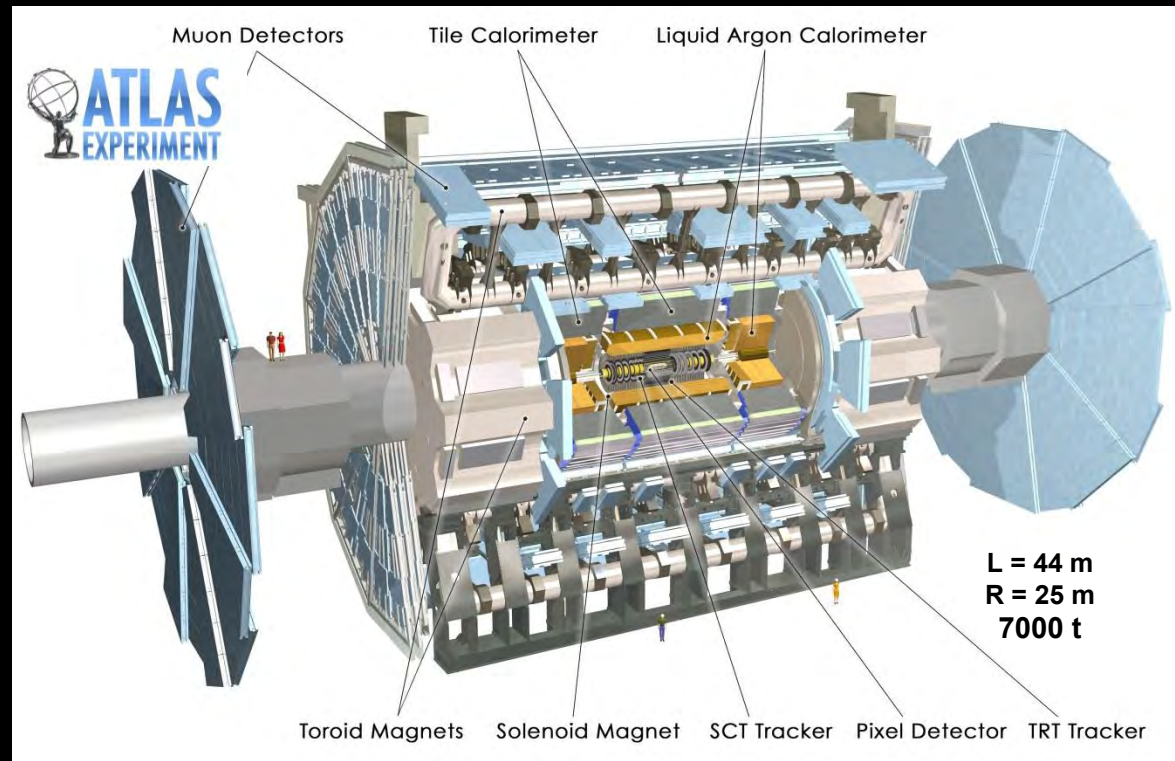
# ATLAS



# ATLAS



Vorwärts Muon Kammern

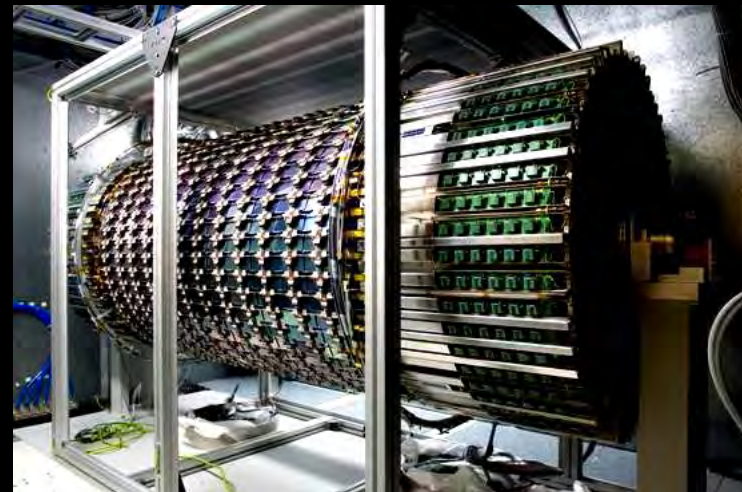


Flüssig Argon Kalorimeter



83 m<sup>3</sup> flüssiges Ar

Silizium-Detektoren

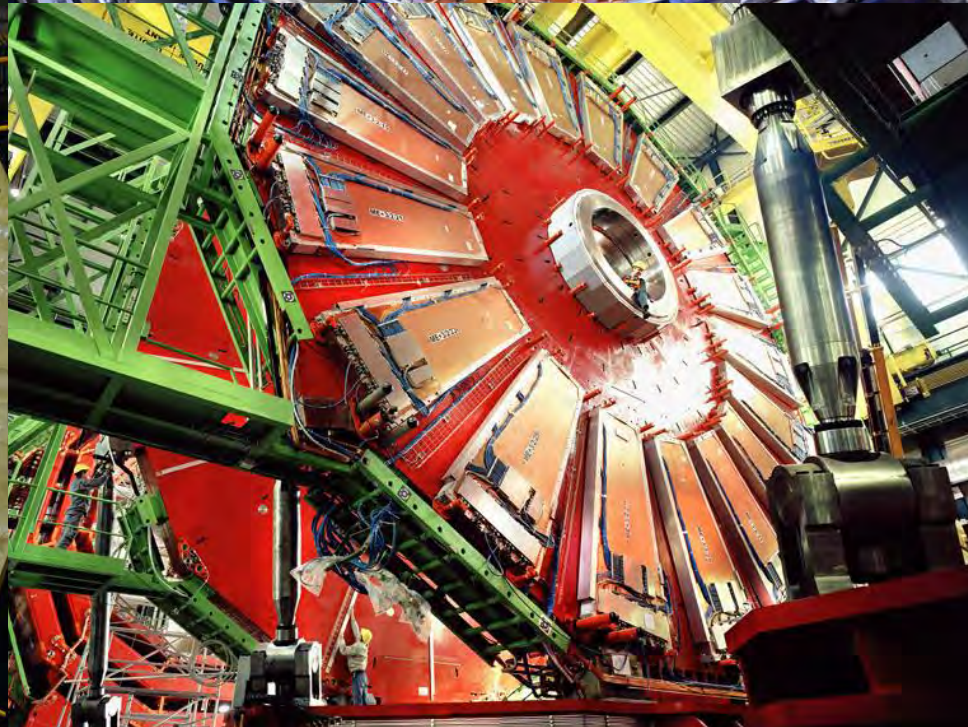
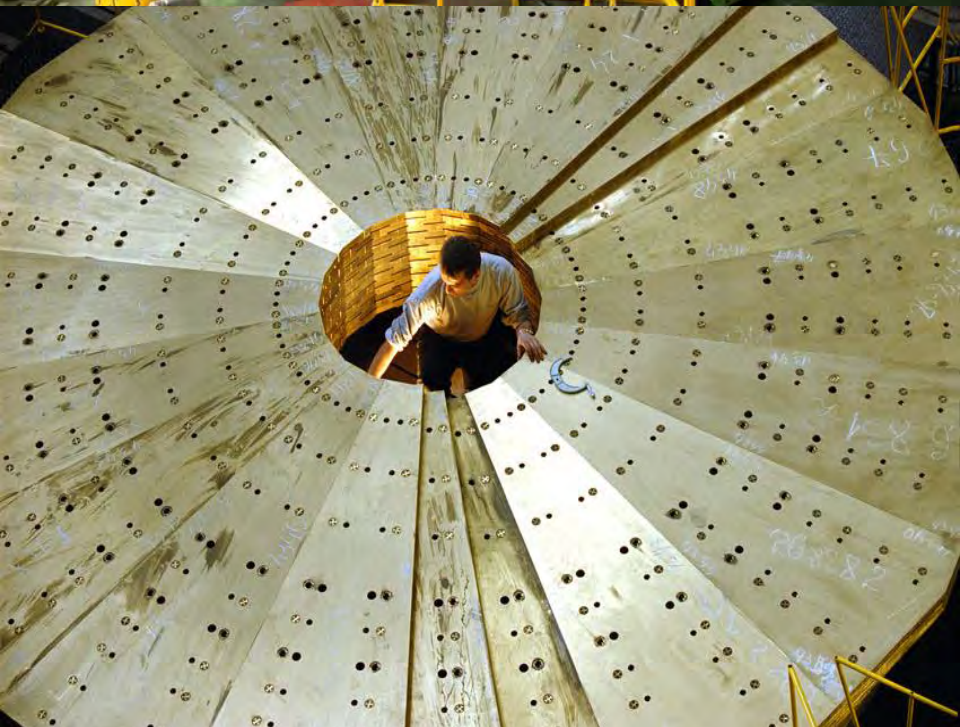
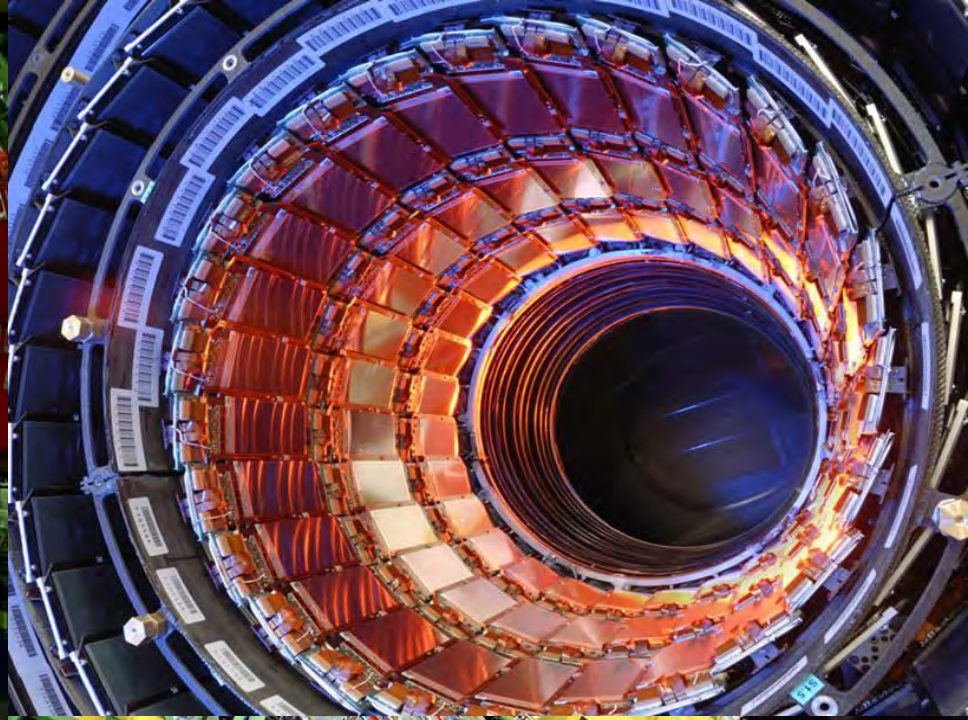


~100 Millionen Kanäle    ~100 m<sup>2</sup> Si



# CMS





**CMS**

75848  $\text{PbWO}_4$  Kristalle

Photon-Nachweis  
Higgs  $\rightarrow \gamma\gamma$



# Vom Web zum Grid

## Rohdaten:

100 Millionen Kanäle  
 $10^9$  Ereignisse/s \* 1 MB =

**1 PB/s**

## Enddaten:

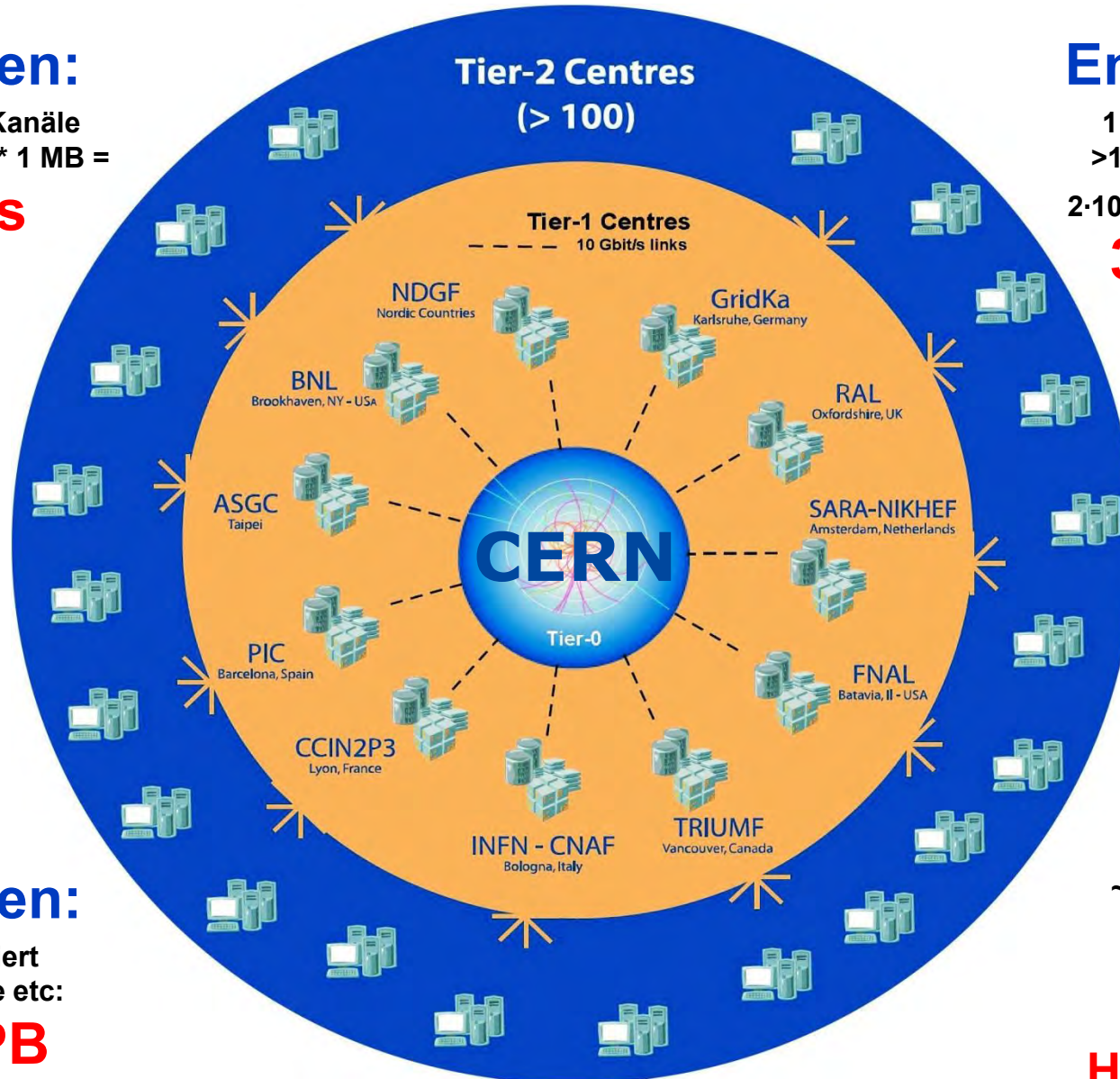
1 kHz \* >1 MB =  
>1 GB/s = 4 TB/h  
 $2 \cdot 10^9$  Ereignisse /a =

**3 PB /a**

## alle Daten:

real + simuliert  
4 Experimente etc:

**~200 PB**



**finde**

~100 Signale/a

**Nadel in  
100.000  
Heuhaufen**

# Erste Kollisionen



21 December 2012 | \$10

# Science

BREAKTHROUGH  
of the YEAR  
The **HIGGS**  
**BOSON**



"All the News  
That's Fit to Print"

# The New York Times

National Edition  
Some bits tonight, some heavy. Total  
6-12 inches north, 3-6 inches central,  
a reaching to 3 inches south. High to  
the 50s. Low to the 30s and 40s.  
Weather map, Page 3-2.

VOL. CLXII...No. 96,066

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Printed in Chicago \$2.50

## ScienceTimes



### Chasing the Higgs

Struggle, and finally triumph, in the search for physics' most elusive particle.

By DENNIS OVERBYE

*Peter Higgs, center, of the University of Edinburgh, was one of the first to propose the particle's existence. From left, physicists at CERN who helped lead the hunt for it: Sau Lan Wu (University of Wisconsin), Joe Incandela (University of California-Santa Barbara), Guido Tonelli (University of Pisa) and Fabiola Gianotti (CERN).*

Peter Higgs, center, of the University of Edinburgh, was one of the first to propose the particle's existence. From left, physicists at CERN who helped lead the hunt for it: Sau Lan Wu, Joe Incandela, Guido Tonelli and Fabiola Gianotti.



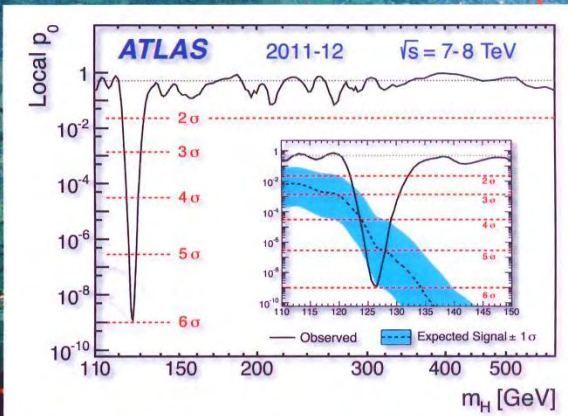
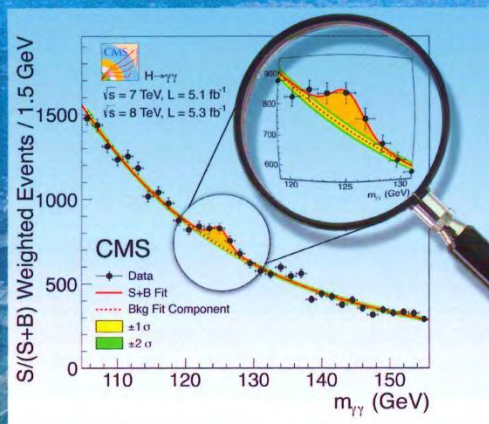
ELSEVIER

# PHYSICS LETTERS B

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

SciVerse ScienceDirect

## Higgs





# Fundamental Physics Prize 2013

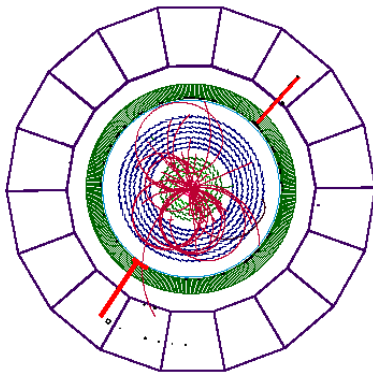
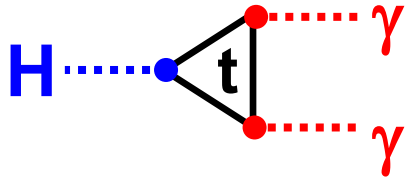
**Milner Foundation**

**3 million \$**

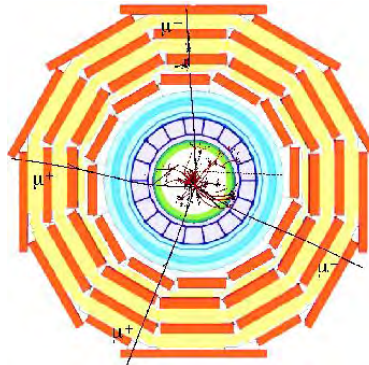
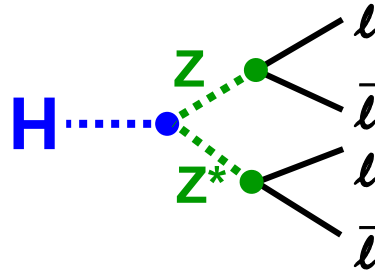
**P Jenni, F Gianotti (ATLAS),  
M Della Negra, T Virdee,  
G Tonelli, J Incandela (CMS)  
Lyn Evans (LHC)**

for their leadership role  
in the scientific endeavour  
that led to the discovery of the  
new Higgs-like particle  
by the ATLAS and CMS collaborations  
at CERN's Large Hadron Collider.

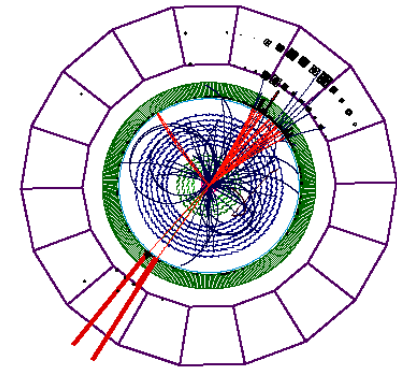
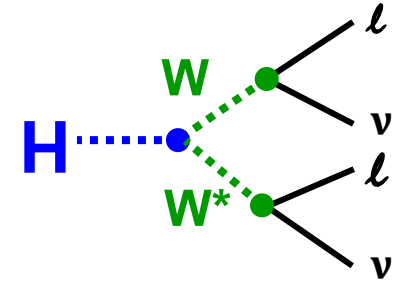
# Higgs-Suche



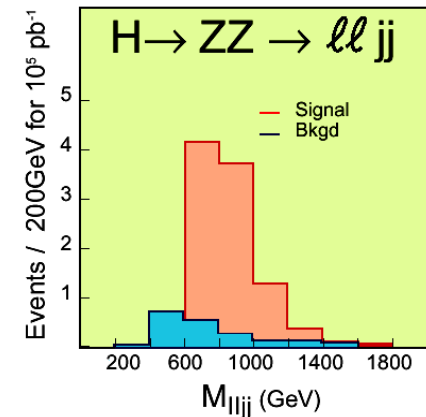
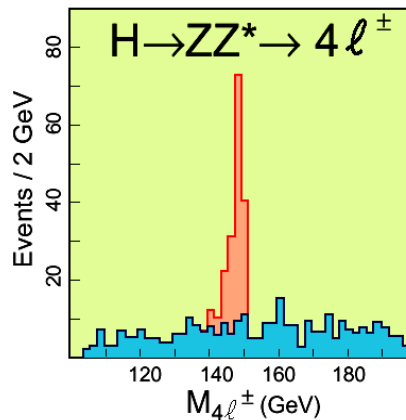
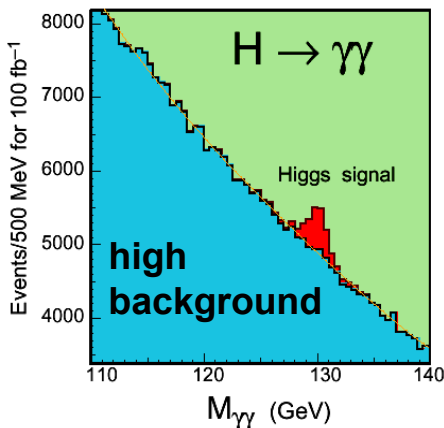
einfach, aber selten:  
 $Br(H \rightarrow \gamma\gamma) = 0.2\%$



sauber, aber selten  
 $Br(H \rightarrow ZZ \rightarrow 4l) \sim 10^{-4}$

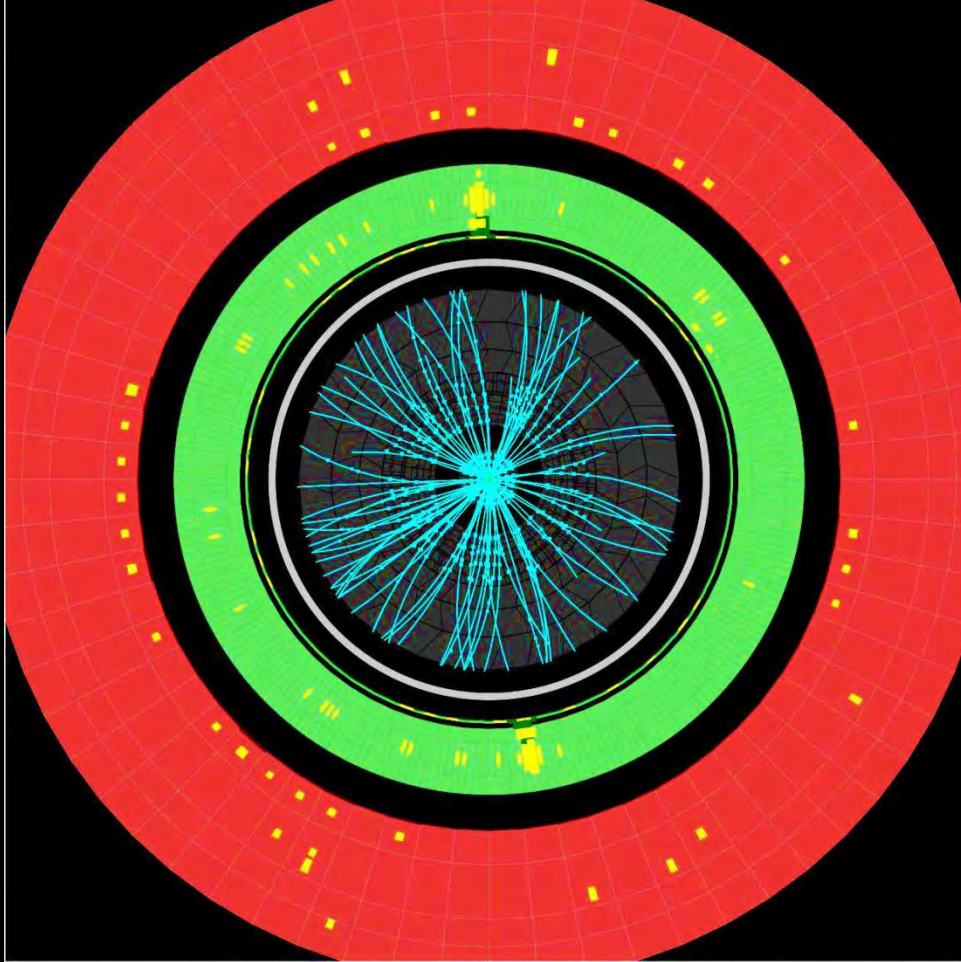


Jets, Leptonen + Neutrinos: breit  
 $Br(H \rightarrow WW) = 22\%$



**H**  
**→**  
 **$\gamma\gamma$**

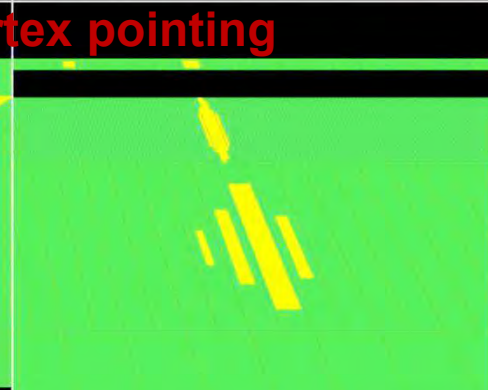
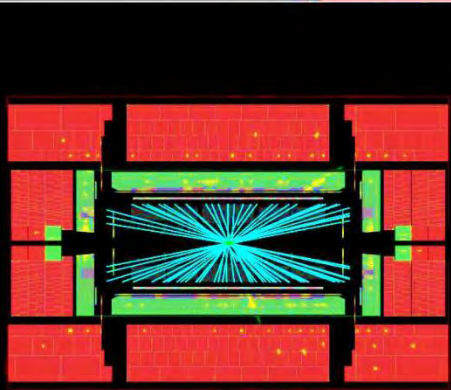
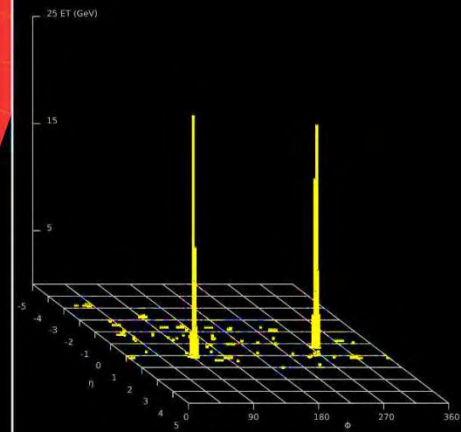
**$m_{\gamma\gamma} =$**   
**126.9 GeV**



 **ATLAS**  
**EXPERIMENT**

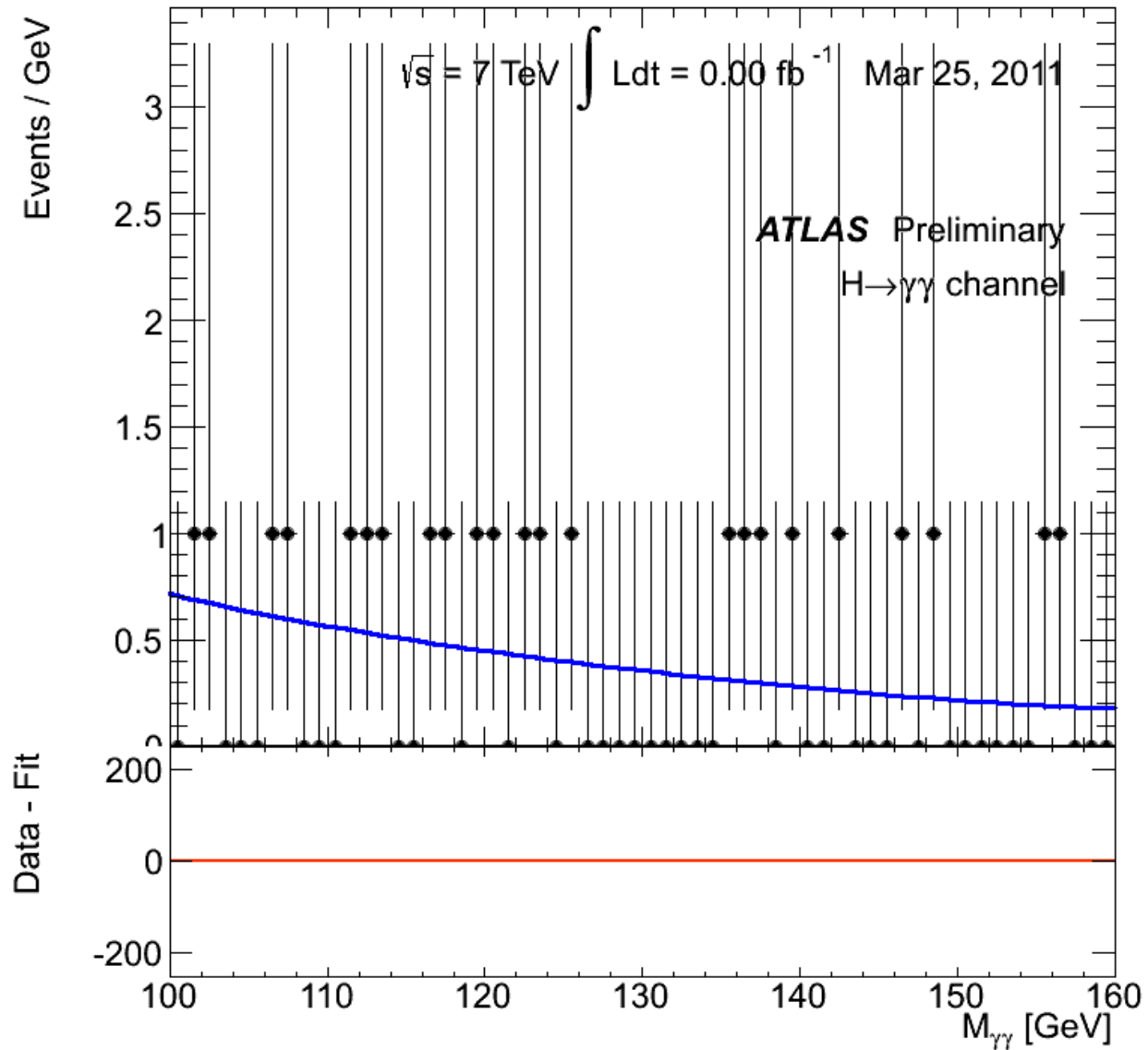
Run Number: 203779, Event Number: 56662314

Date: 2012-05-23 22:19:29 CEST



**vertex pointing**

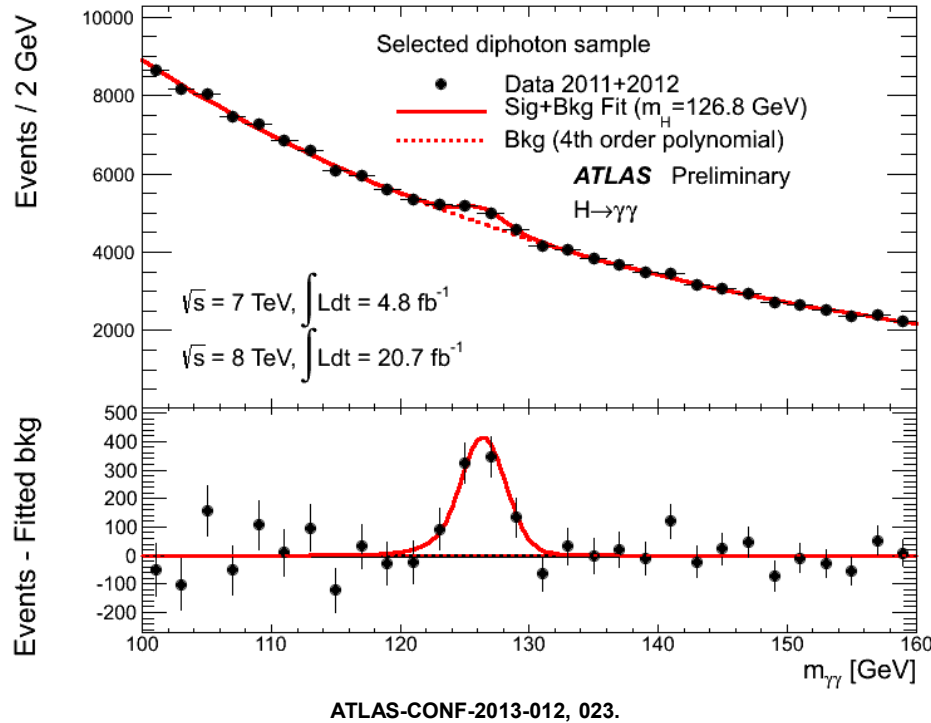
# Higgs $\rightarrow \gamma\gamma$



# Higgs $\rightarrow \gamma\gamma$

## ATLAS

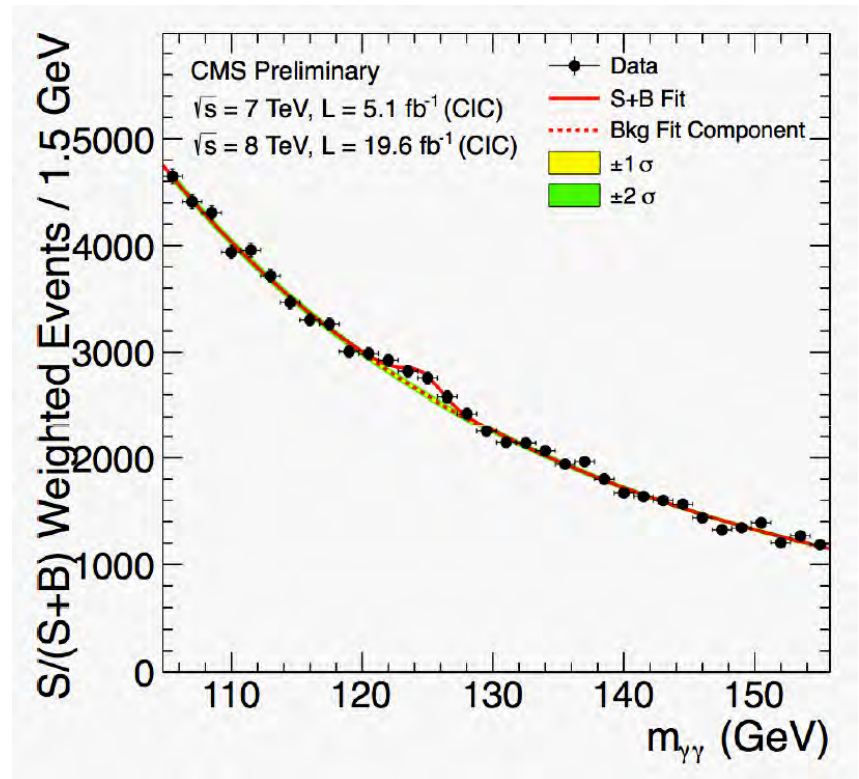
## CMS



**7.4  $\sigma$  Signifikanz**

**1.6 $\pm$ 0.3 x Standard-Modell**

**Masse = 126.8  $\pm$  0.2 $_{\text{stat}}$   $\pm$  0.7 $_{\text{syst}}$  GeV**



**3.2  $\sigma$  Signifikanz**

**0.8 $\pm$ 0.3 x Standard-Modell**

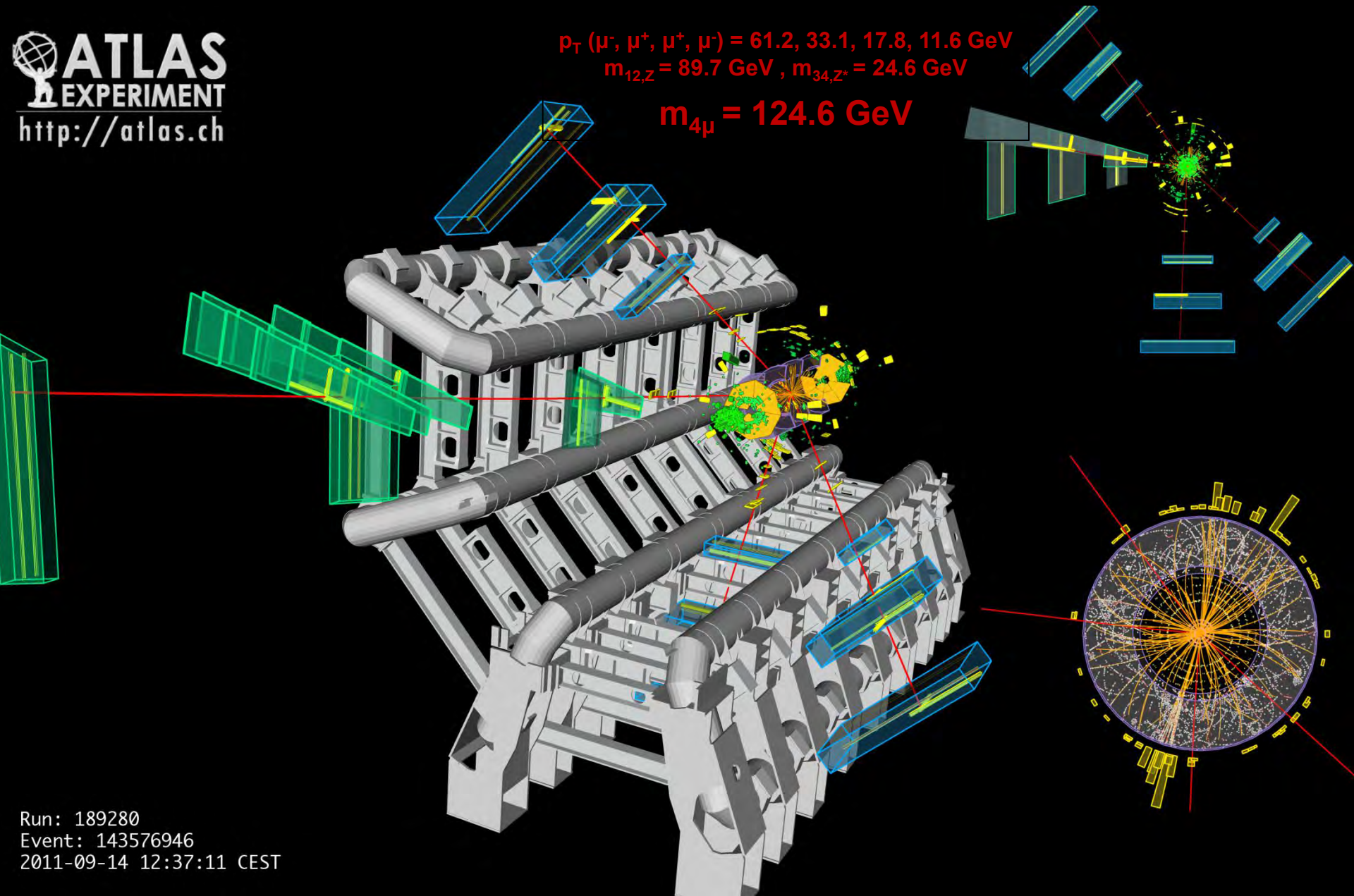
**Masse = 125.4  $\pm$  0.5 $_{\text{stat}}$   $\pm$  0.6 $_{\text{syst}}$  GeV**

# H $\rightarrow$ 4 $\mu$ Kandidat

 **ATLAS**  
EXPERIMENT  
<http://atlas.ch>

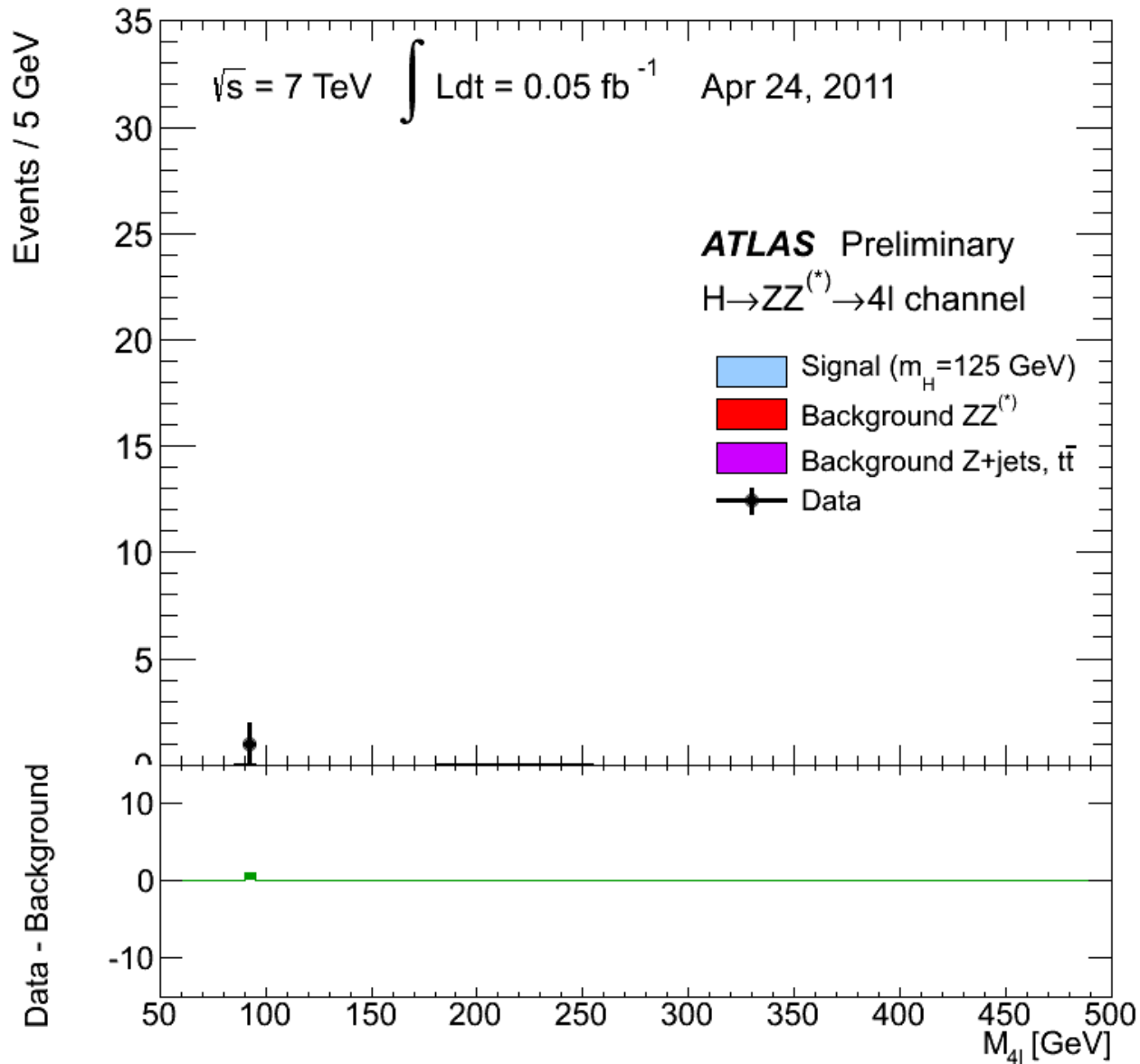
$p_T(\mu^-, \mu^+, \mu^+, \mu^-) = 61.2, 33.1, 17.8, 11.6$  GeV  
 $m_{12,Z} = 89.7$  GeV,  $m_{34,Z^*} = 24.6$  GeV

$m_{4\mu} = 124.6$  GeV



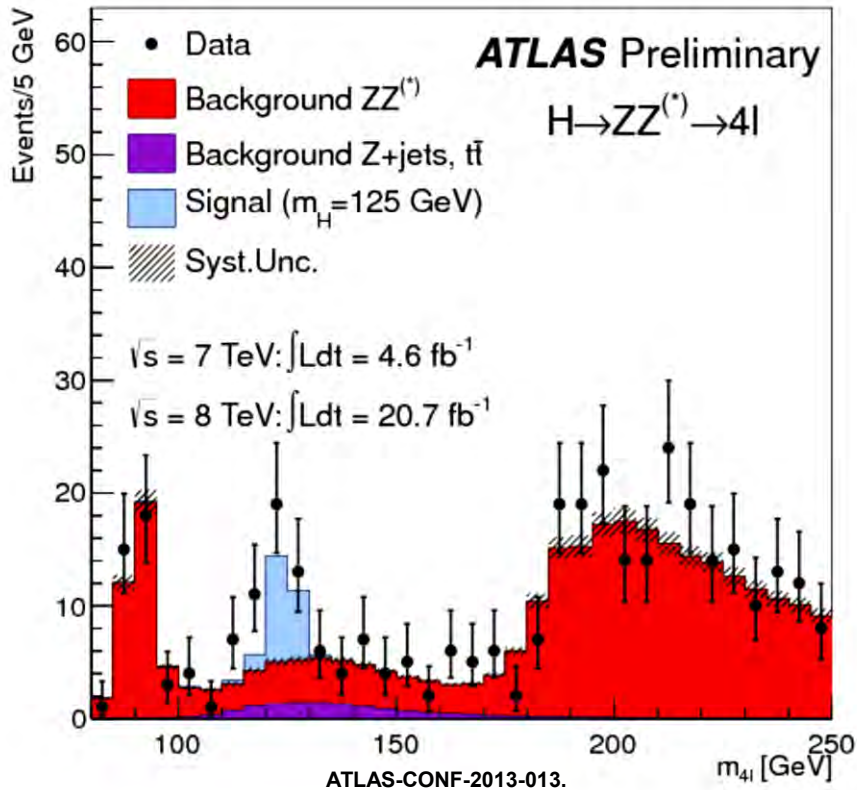
Run: 189280  
Event: 143576946  
2011-09-14 12:37:11 CEST

# Higgs $\rightarrow$ ZZ $\rightarrow$ 4 $\ell$



# Higgs $\rightarrow$ ZZ $\rightarrow$ 4 $\ell$

## ATLAS



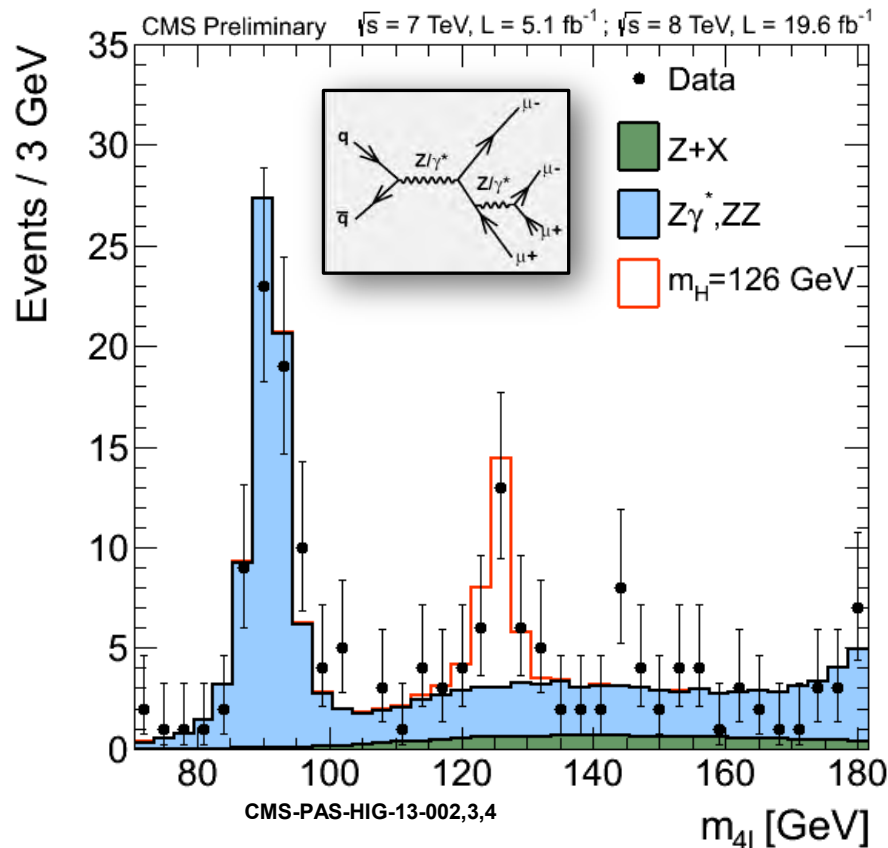
Signifikanz **6.6  $\sigma$**

Masse = **124.3  $\pm$  0.6<sub>stat</sub>  $\pm$  0.4<sub>syst</sub> GeV**

**1.7 $\pm$ 0.5 x Standardmodell**

32 Events gesehen, erwartet S+B = 16 $\pm$ 2 + 11 $\pm$ 1

## CMS



Signifikanz **6.7  $\sigma$**

Masse = **125.8  $\pm$  0.5<sub>stat</sub>  $\pm$  0.2<sub>syst</sub> GeV**

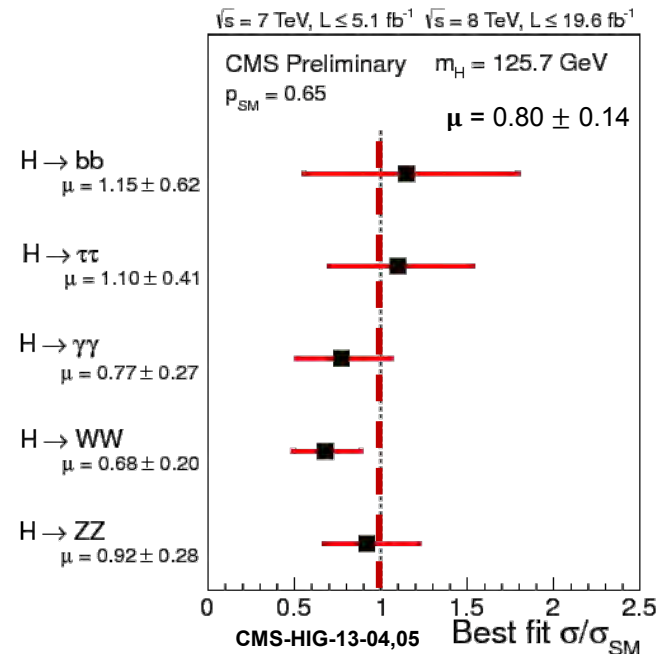
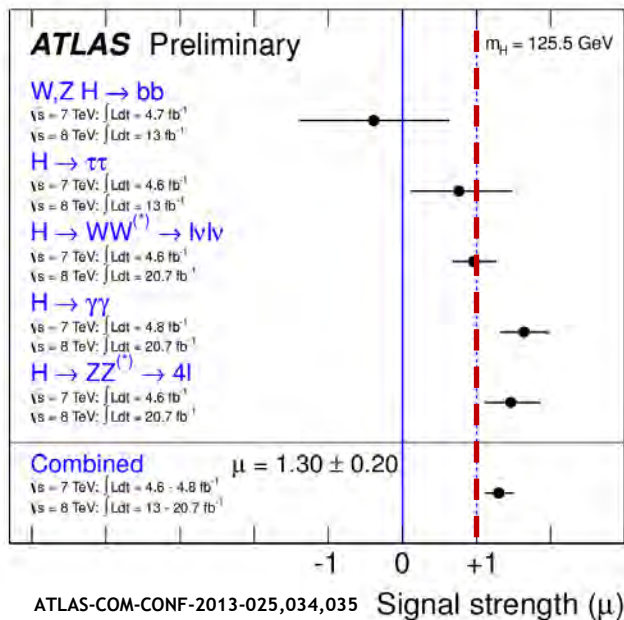
**0.9 $\pm$ 0.3 x Standardmodell**

Spin 0<sup>+</sup> bevorzugt über 0<sup>-</sup>, 1, 2 mit  $\sim 2 \sigma$



# Ist es das Higgs ?

Signatur:  
Kopplung  $\sim$  Masse

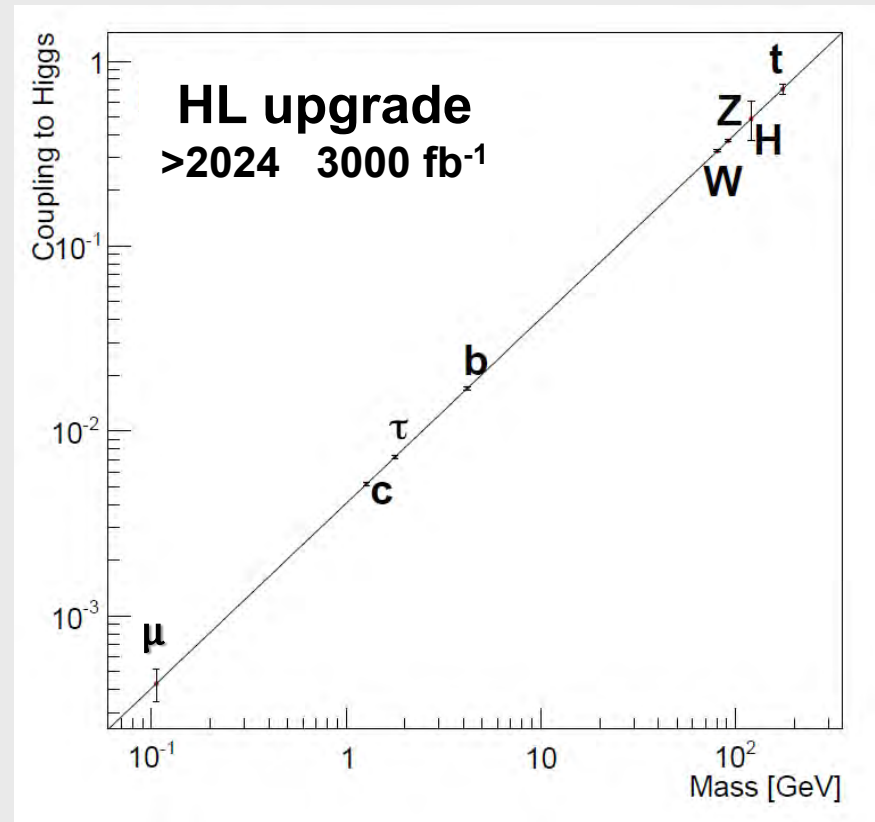
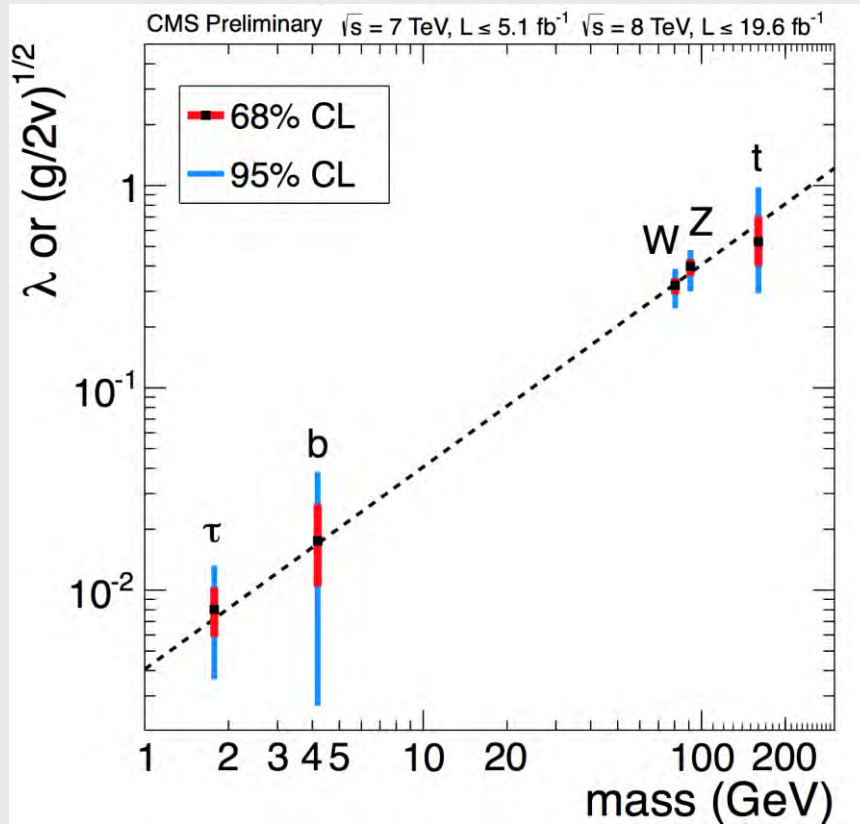


$\mu = \text{beobachtet} / \text{Standard-Modell}$

$$\mu_{LHC} = 1.0 \pm 0.1$$

# Ist es das Higgs?

2013 LHC >2024



# Higgs - ein neues Feld



Spin	Feld	abgeleitet	fundamental
0	Skalar	Temperatur, Druck, ...	Higgs, Inflation, Dunkle Energie
1	Vektor	Strömung: Wind, Wasser	Kraft: Elektro-Magnetisch
2	Tensor	Elastizität	Kraft: Gravitation
$\frac{1}{2}$	Spinor		Bausteine: Elektron, Quarks (Fermionen)

# Higgs Spin

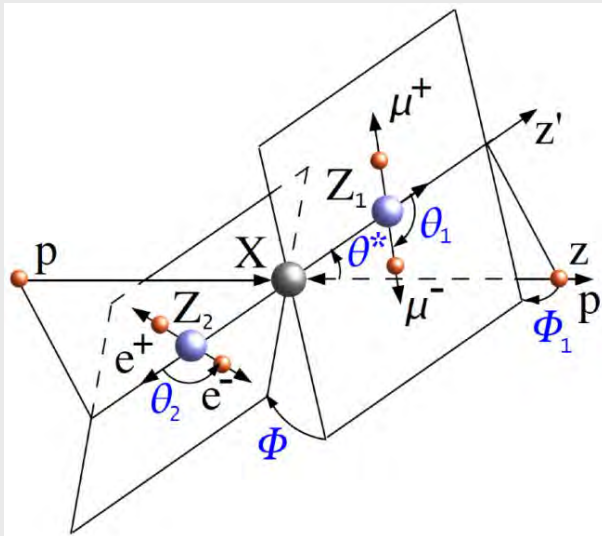
- elektroschwache Symmetrie-Brechung **global** in Raum + Zeit
- **keine** bevorzugte Richtung im Vakuum  
**kein Spin** des Vakuum-Grundzustands !

• **Higgs: erstes fundamentales Skalar-Feld !**

$$H \rightarrow \gamma\gamma, H \rightarrow ZZ^* \rightarrow 4l, H \rightarrow WW^* \rightarrow ll\nu\nu$$

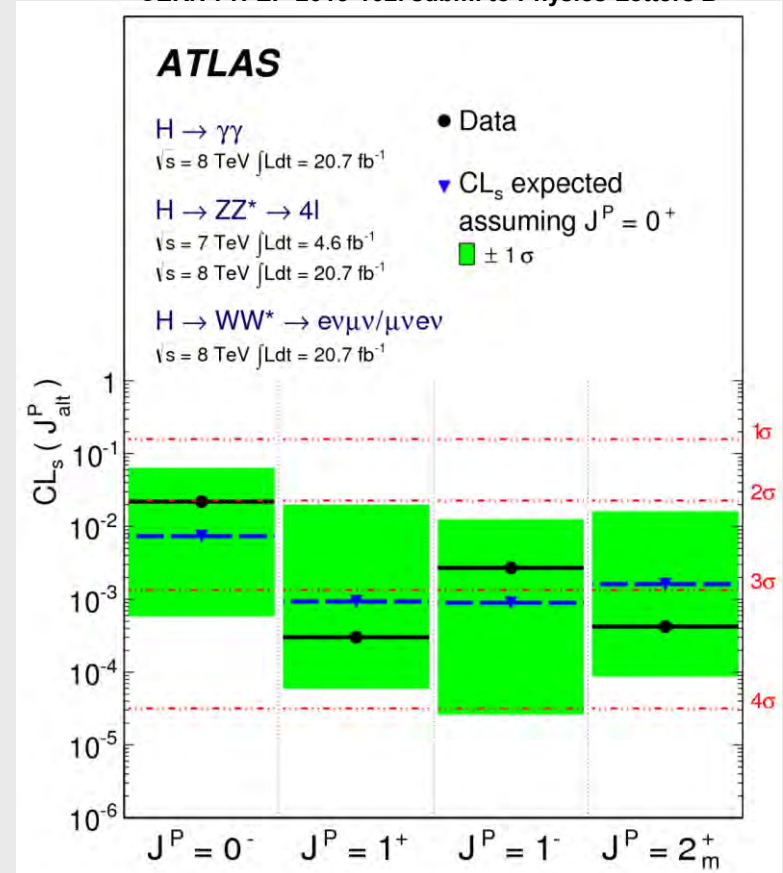
**Spin  $\neq 0$  ausgeschlossen zu >99%**

**Spin =  $0^+$  favorisiert zu 98%**



$J^P$	CL reject	Kanäle
$0^-$	<b>97.8</b> %	ZZ
$1^+$	<b>99.97</b> %	ZZ, WW
$1^-$	<b>99.7</b> %	ZZ, WW
$2^+$	<b>&gt;99.9</b> %	ZZ, WW, $\gamma\gamma$

CERN-PH-EP-2013-102. subm. to Physics Letters B



# LHC - wie weiter ?

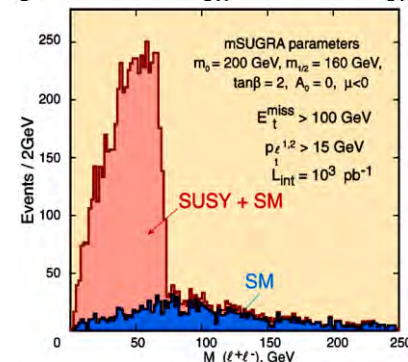
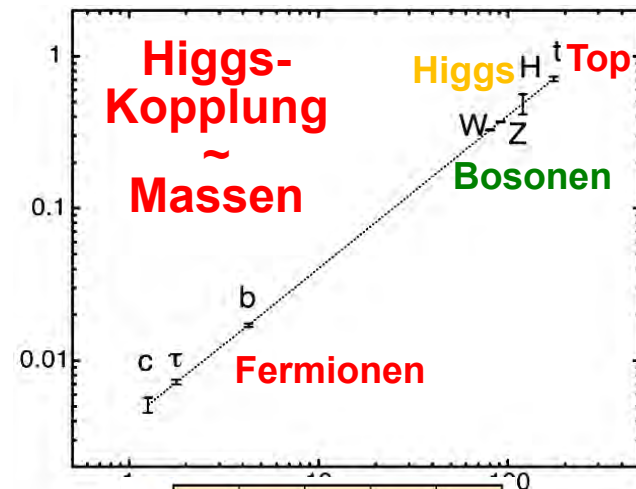
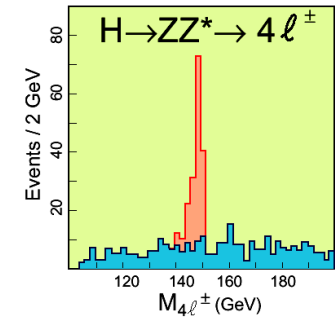
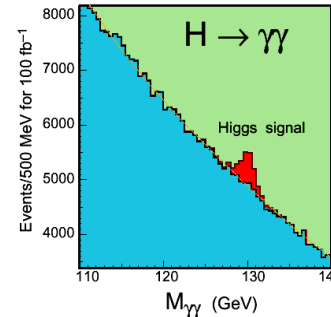
Reparatur 2014  
Restart 2015

-  $E = 2 \times 7 \text{ TeV}$  , volle Intensität =>  
volles **Entdeckungspotential**

**erforsche  
die neue Welt  
der Skalare:**

Higgs Spin, Kopplungen, ...

- **SUSY, wo bist Du:**  $>1 \text{ TeV}$   
mehr (geladene) Higgse ?
- **Extra Dimensionen:**  $>2 \text{ TeV}$  ?





BIG BANG OCEAN

SUPERSYMMETRY REEF

DARK MATTER LANDMASS

HIGGS ISLAND

RUNNING PASSAGE

# Terra Incognita zu neuen Ufern

SEA OF BIG MISTRIES

SEA OF SMALL MYSTERIES

LAND OF ULTIMATE UNIFICATION

EXTRA DIMENSIONS ARCHIPELAGO

QUARK SEA

STANDARD MODEL HARBOUR

KNOWN TERRITORY

DARK ENERGY AELSTROM

SEA OF THEORIES

Knowledge Frontier

Cape Antimatter

Mount



**Kolumbus  
suchte Indien.  
Er entdeckte  
Amerika.**



# Expect the Unexpected