

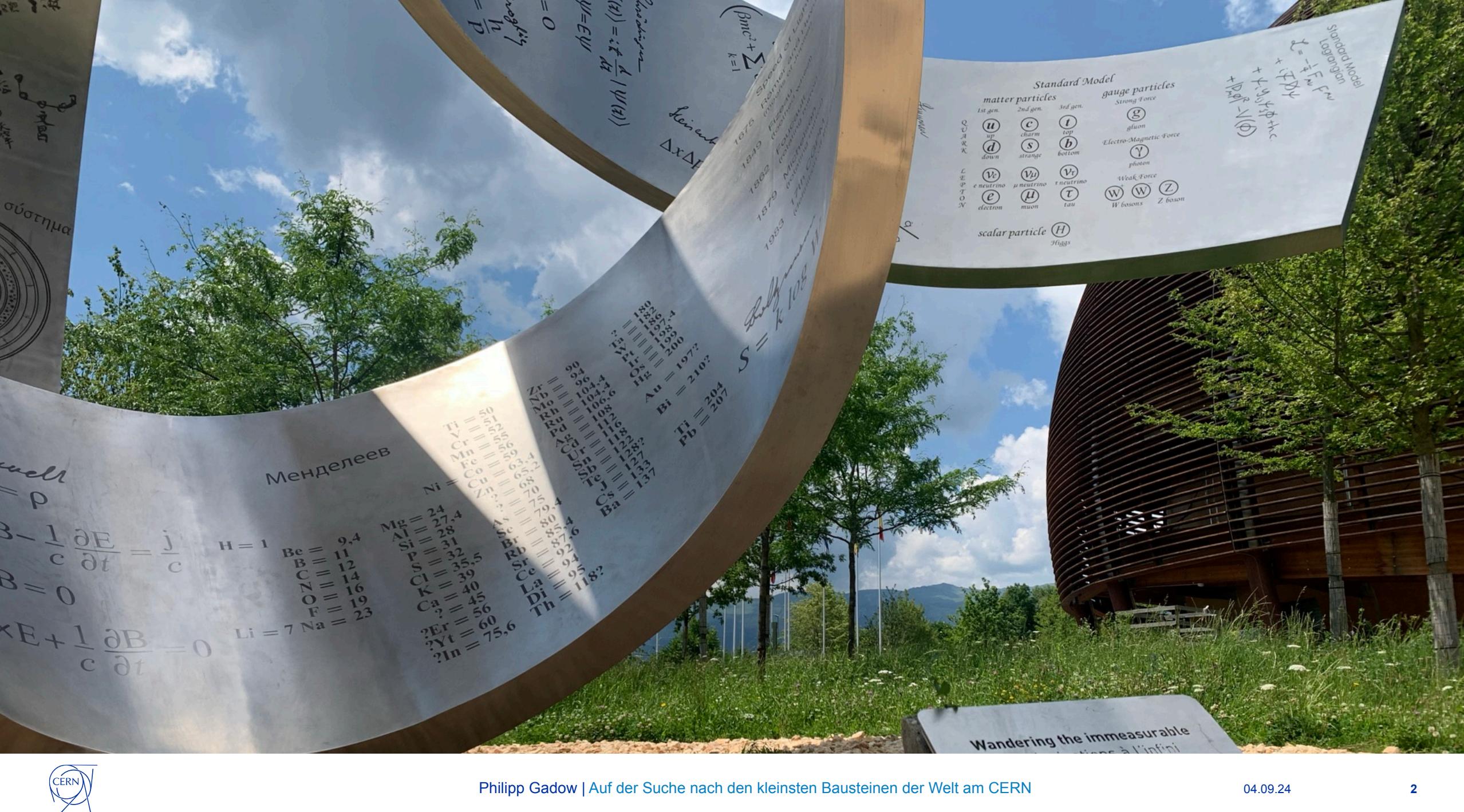


Auf der Suche nach den kleinsten Bausteinen der Welt am CERN

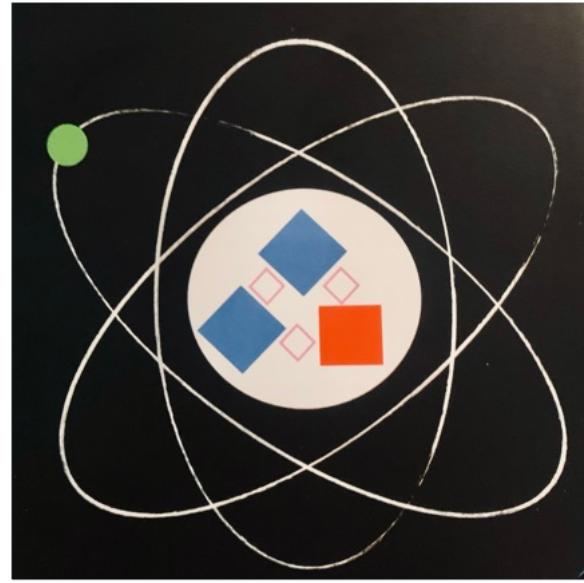
Dr. Philipp Gadow (CERN)

Abendvortrag, Sommerakademie Annecy, 04.09.2024

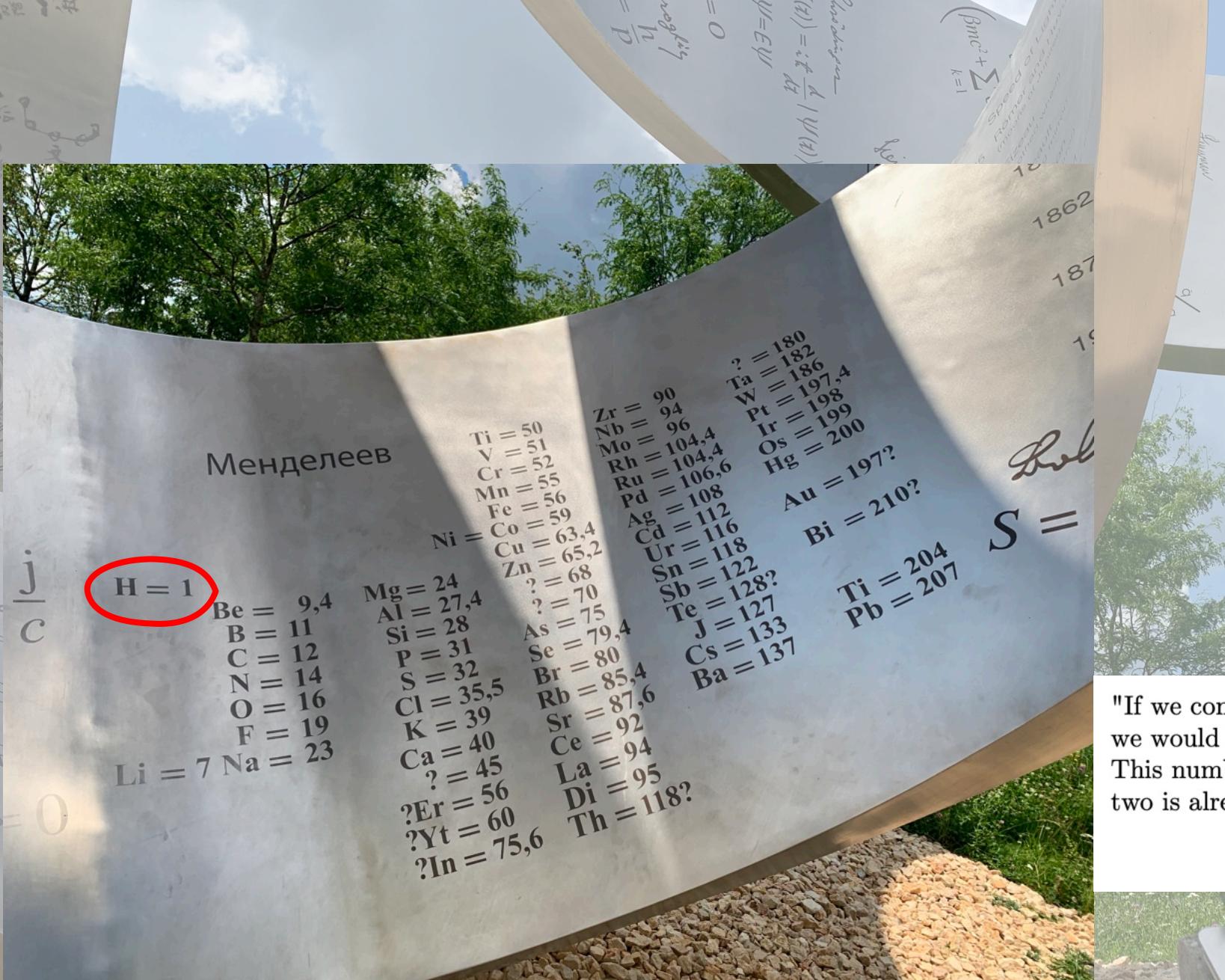




Wasserstoffatom



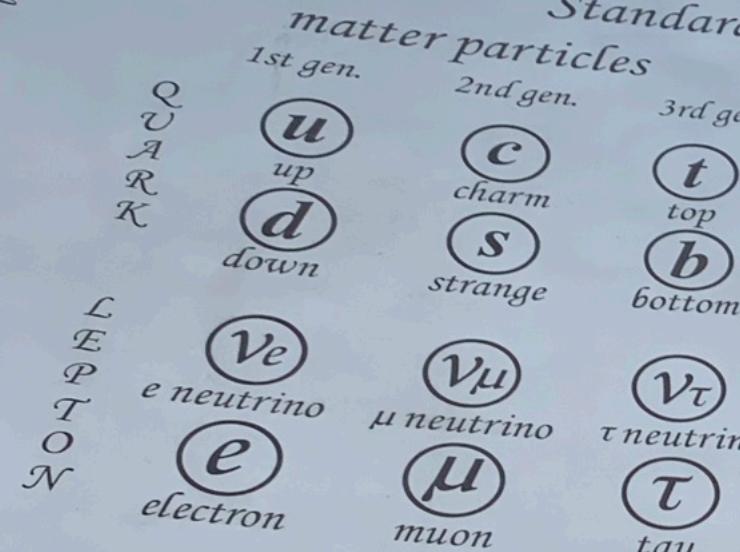
Source: "Particle Physics for Babies", L. Corpe



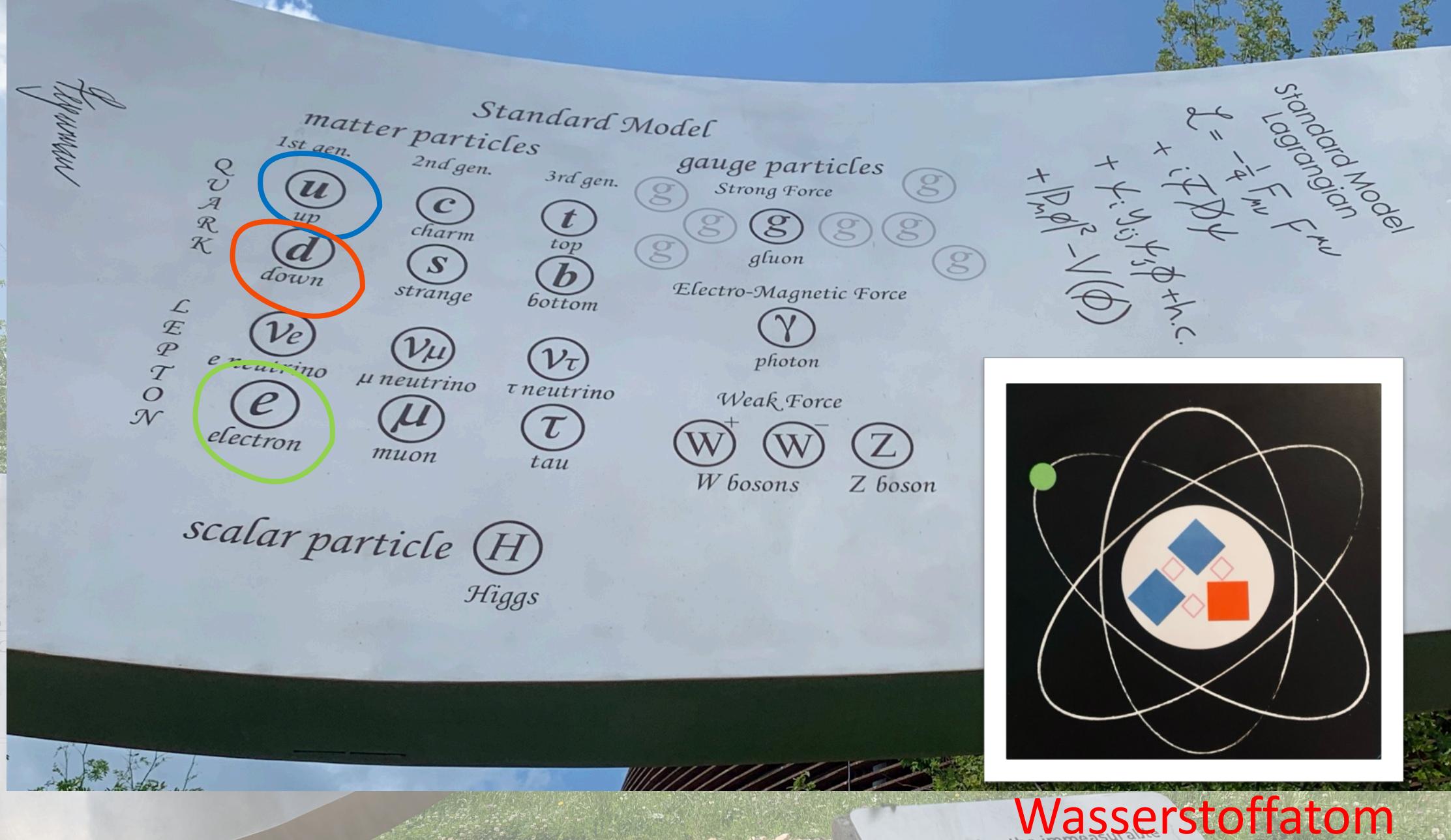
Standard Model
Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} i \gamma^\mu \partial_\mu \psi + \bar{\phi} \nabla^2 \phi + h.c.$$

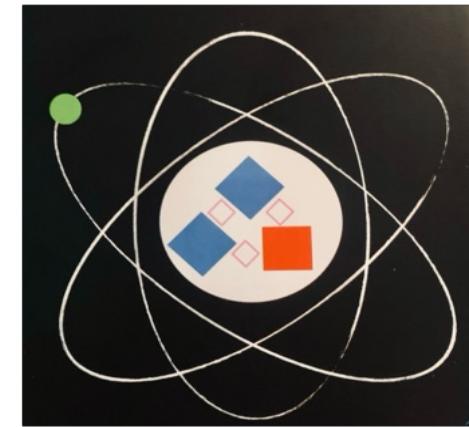
Standard Model
matter particles



Wandering the immeasurable
à l'infini

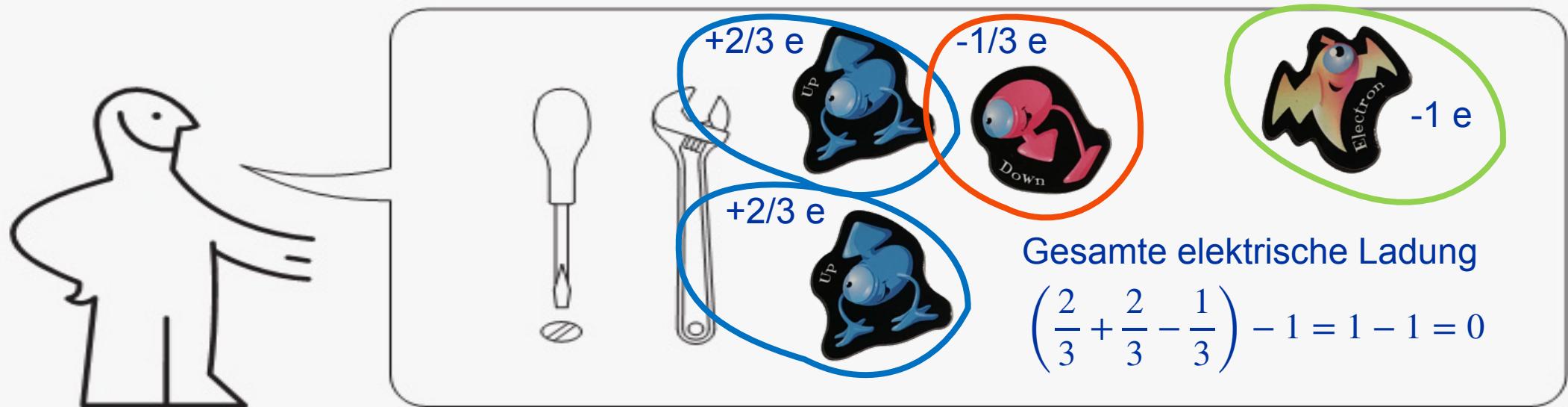


i



Åtöm

1. Baue als Kern Proton zusammen aus 2 Up-Quarks + 1 Down-Quark
2. Füge zum Kern ein Elektron hinzu
3. Fertig ist das Atom



Was sind Elementarteilchen?

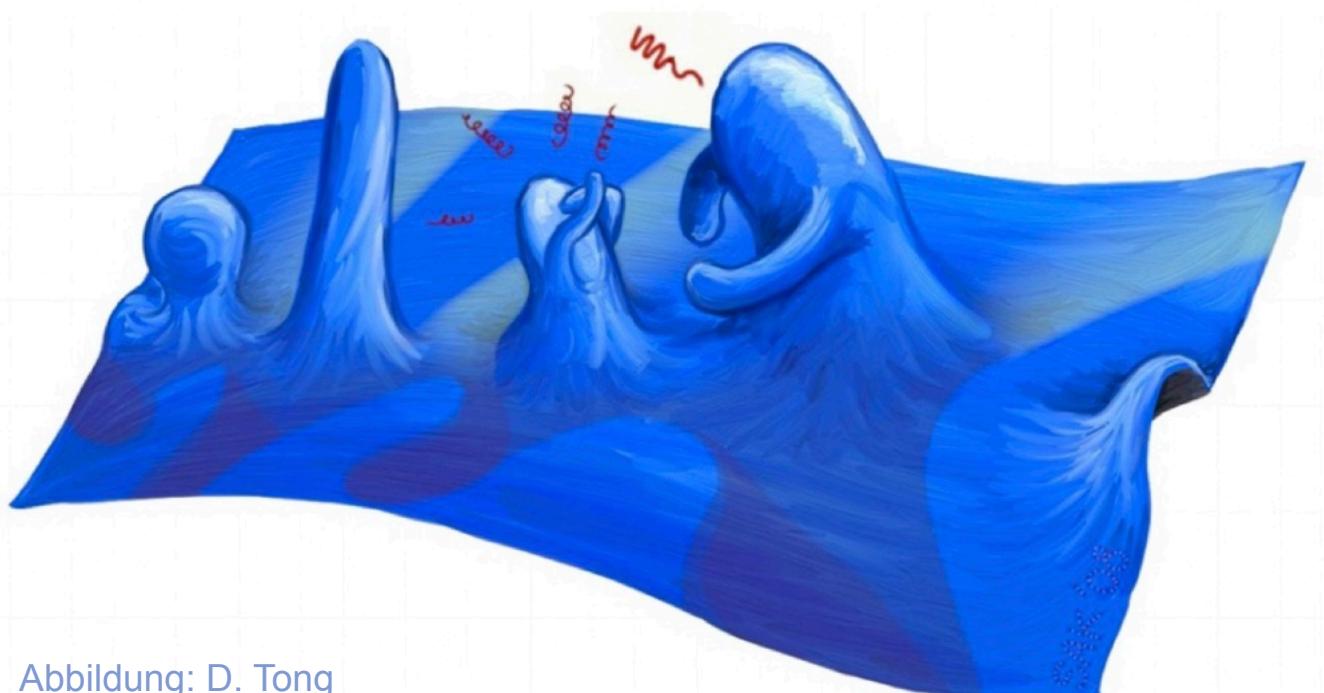


Abbildung: D. Tong

Teilchen sind Anregungen zugrunde liegender Quantenfelder.

Differentialgleichungen beschreiben wie sich Teilchen in der Zeit entwickeln.



Klassische Mechanik

$$m \frac{\partial^2}{\partial t^2} \vec{x} = \vec{F}(\vec{x}, t)$$



Quantenmechanik

$$i\hbar \frac{\partial}{\partial t} \Psi(\mathbf{x}, t) = \hat{H} \Psi(\mathbf{x}, t)$$



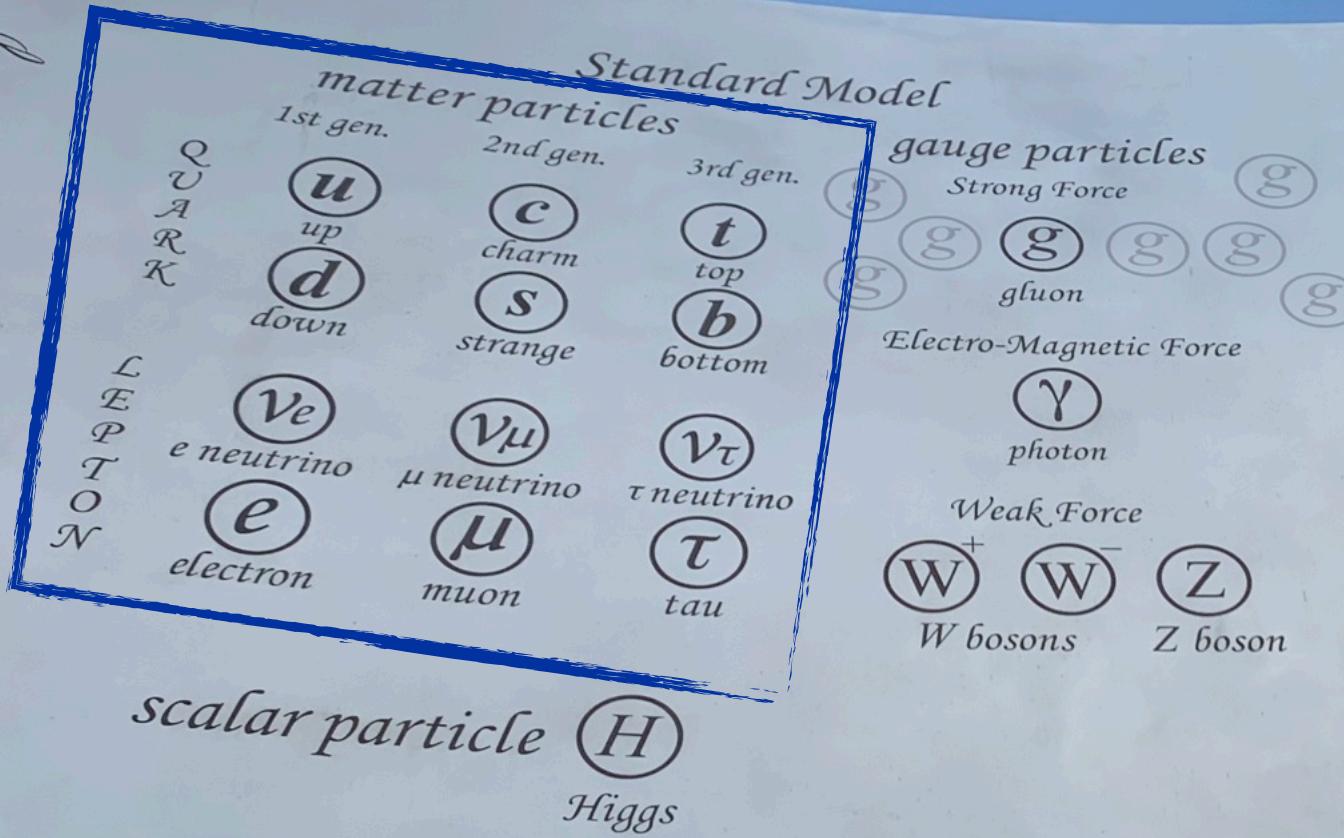
$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} i \gamma^\mu \partial_\mu \psi + \text{h.c.}$$

Dirac Gleichung

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$



Wandering the immeasurable
à l'infini

Was sind Kraftfelder?

Kräfte sind ebenfalls durch Felder begründet und haben zugeordnete Teilchen:

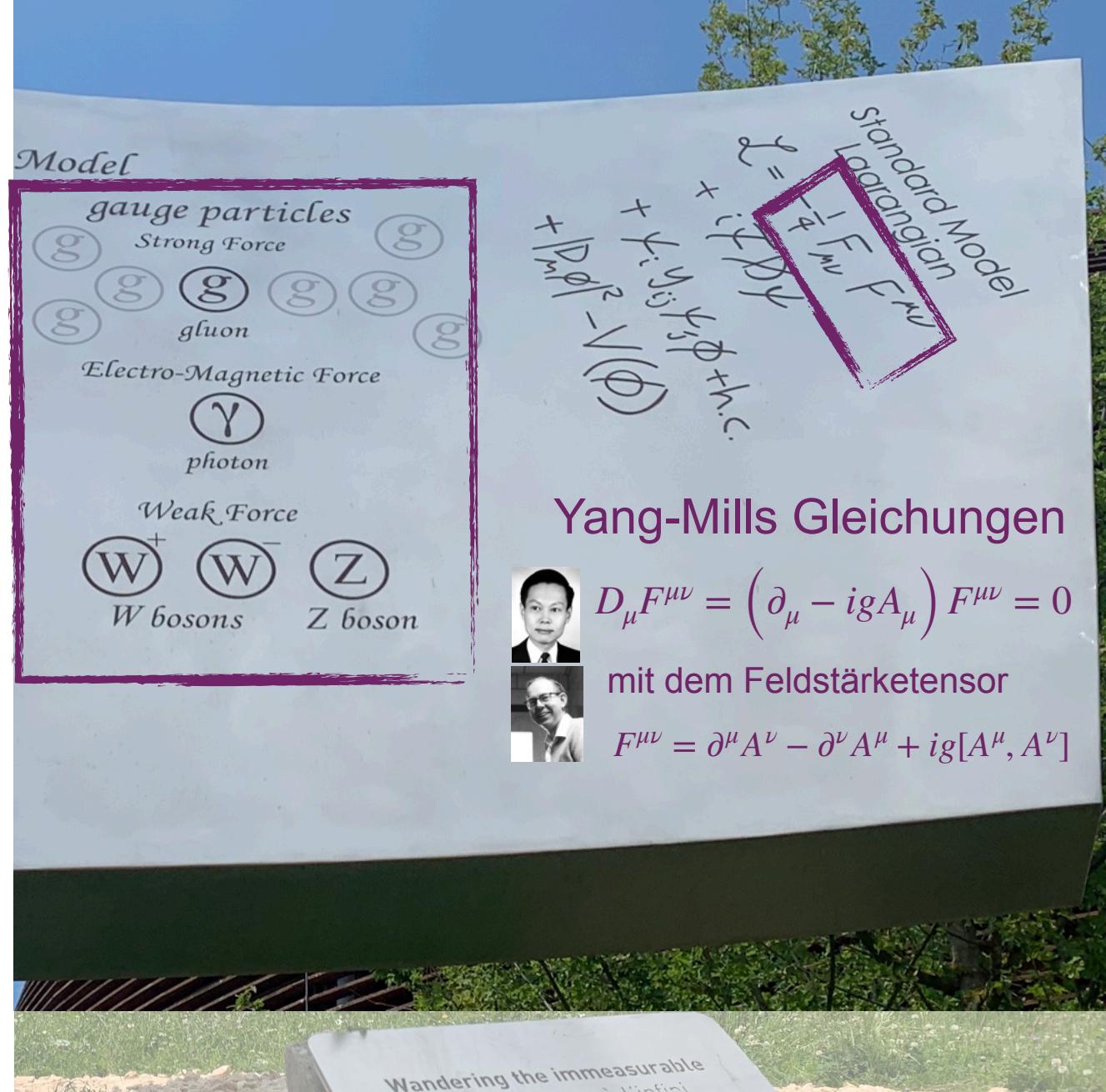
Starke Kraft: Gluon (8 Gluonen)

Schwache Kraft: W^+ , W^- , Z Boson

Elektromagnetische Kraft: Photon



A_μ



Yang-Mills Gleichungen

$$D_\mu F^{\mu\nu} = (\partial_\mu - ig A_\mu) F^{\mu\nu} = 0$$

mit dem Feldstärketensor

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu + ig [A^\mu, A^\nu]$$

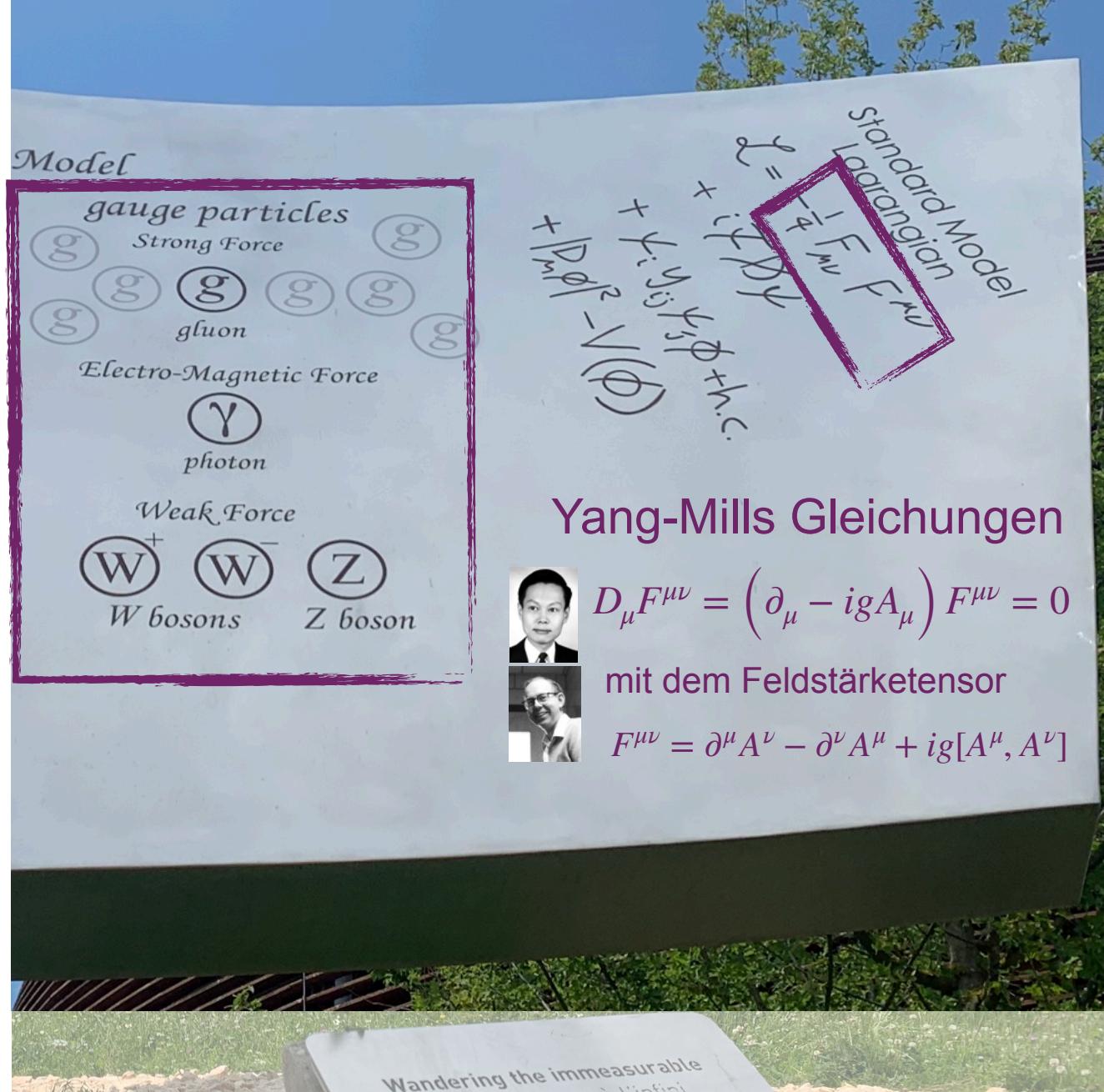
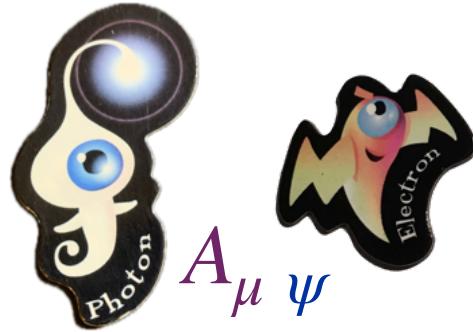
Was sind Kraftfelder?

Kräfte sind ebenfalls durch Felder begründet und haben zugeordnete Teilchen:

Starke Kraft: Gluon (8 Gluonen)

Schwache Kraft: W^+ , W^- , Z Boson

Elektromagnetische Kraft: Photon

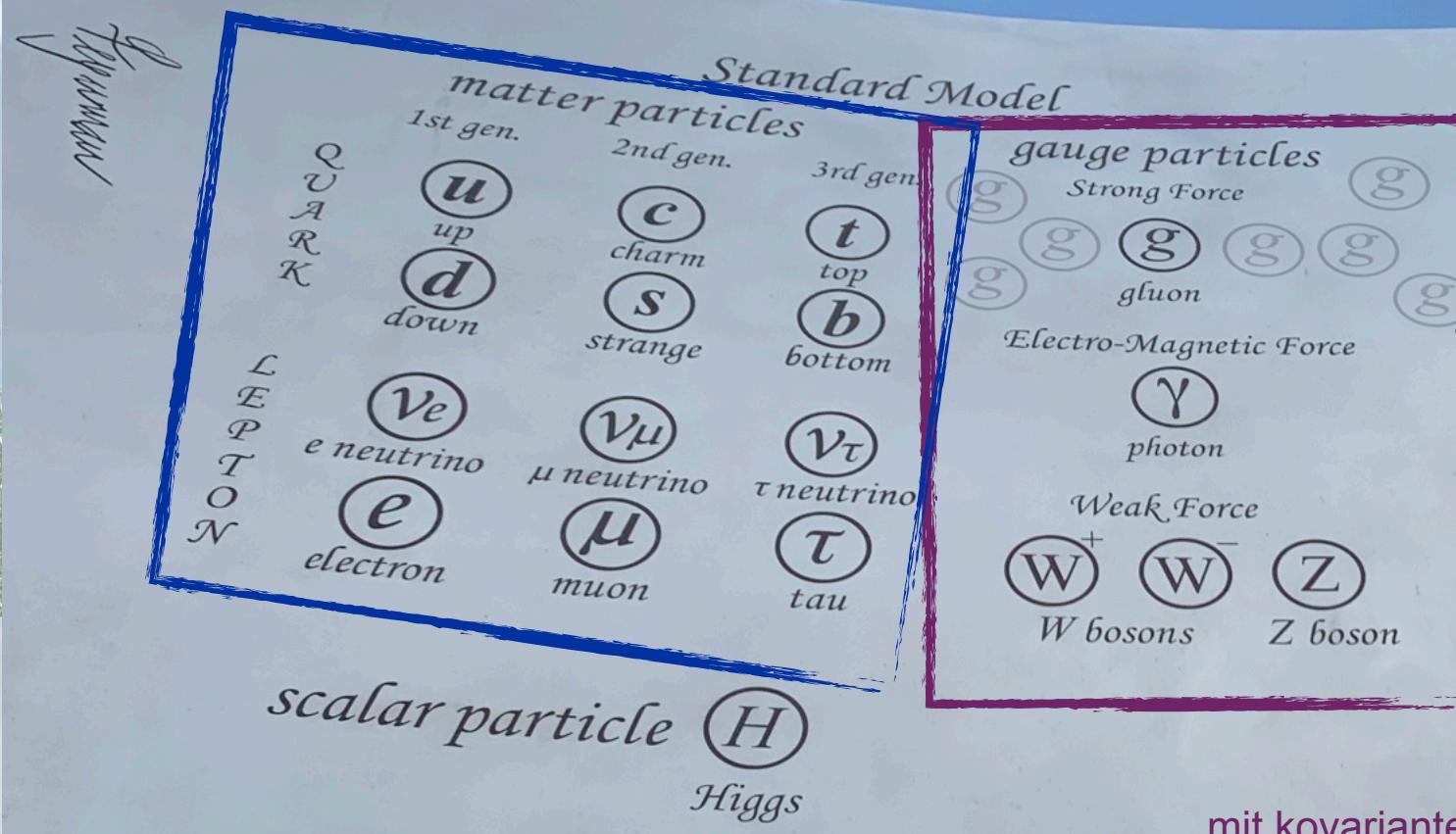


Yang-Mills Gleichungen

$$D_\mu F^{\mu\nu} = (\partial_\mu - igA_\mu) F^{\mu\nu} = 0$$

mit dem Feldstärketensor

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu + ig[A^\mu, A^\nu]$$



Standard Model Lagrangian

$$\mathcal{L} = \bar{\psi} i\gamma^\mu (\partial_\mu - igA_\mu) \psi + \frac{1}{2} D_\mu g_{\mu\nu} D^\nu + \dots + \text{h.c.}$$

Dirac Gleichung

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

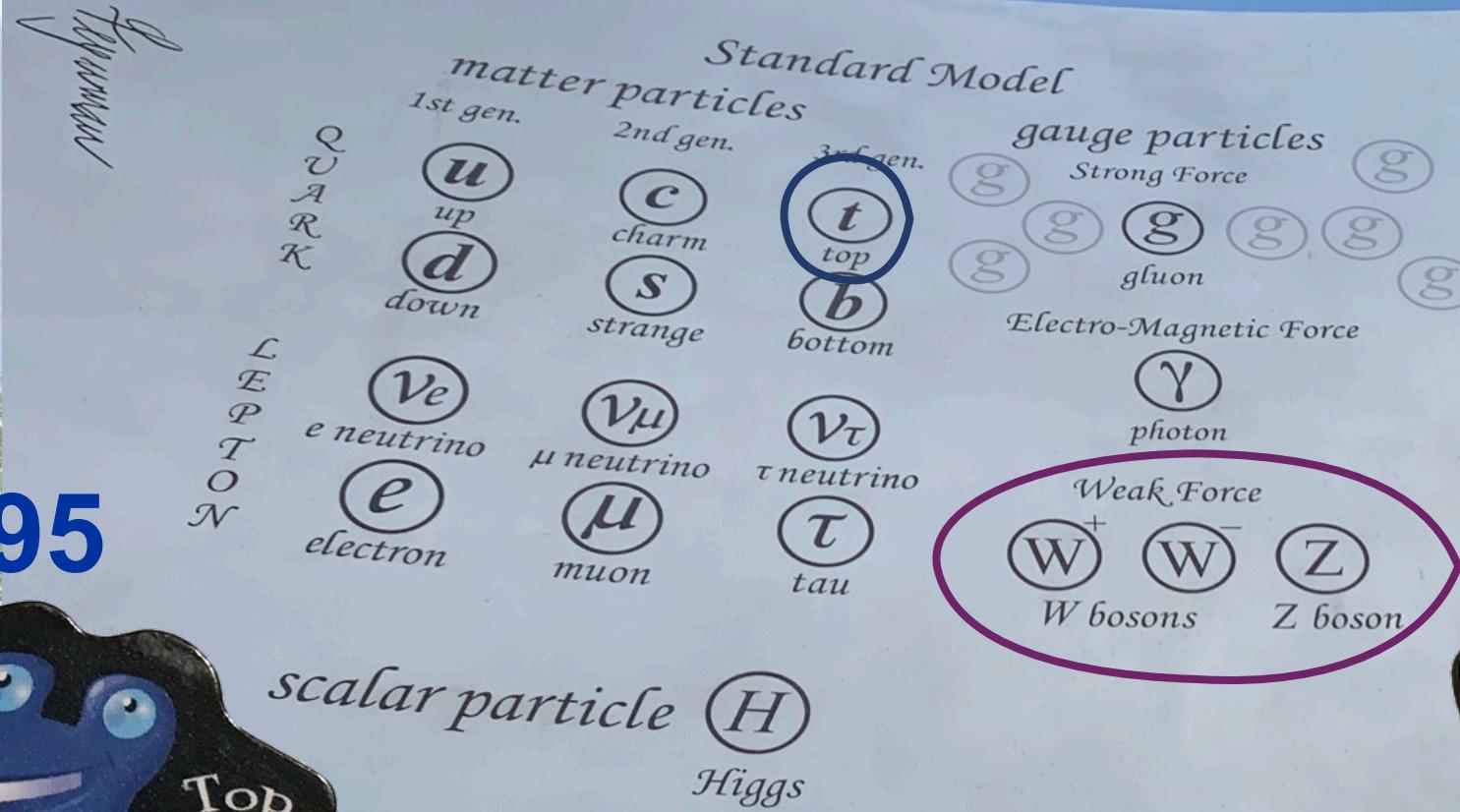
Minimale Kopplung

$$(i\gamma^\mu D_\mu - m)\psi = 0$$

mit kovarianter Ableitung $D_\mu = (\partial_\mu - igA_\mu)$

Wechselwirkungen

1995



1983

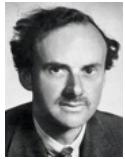


Wie entdecken wir neue
Teilchen?

Wandering the immeasurable
à l'infini

Theorie

Materienteilchen haben Masse (m).



Dirac Gleichung
 $(i\gamma^\mu \partial_\mu - m)\psi = 0$



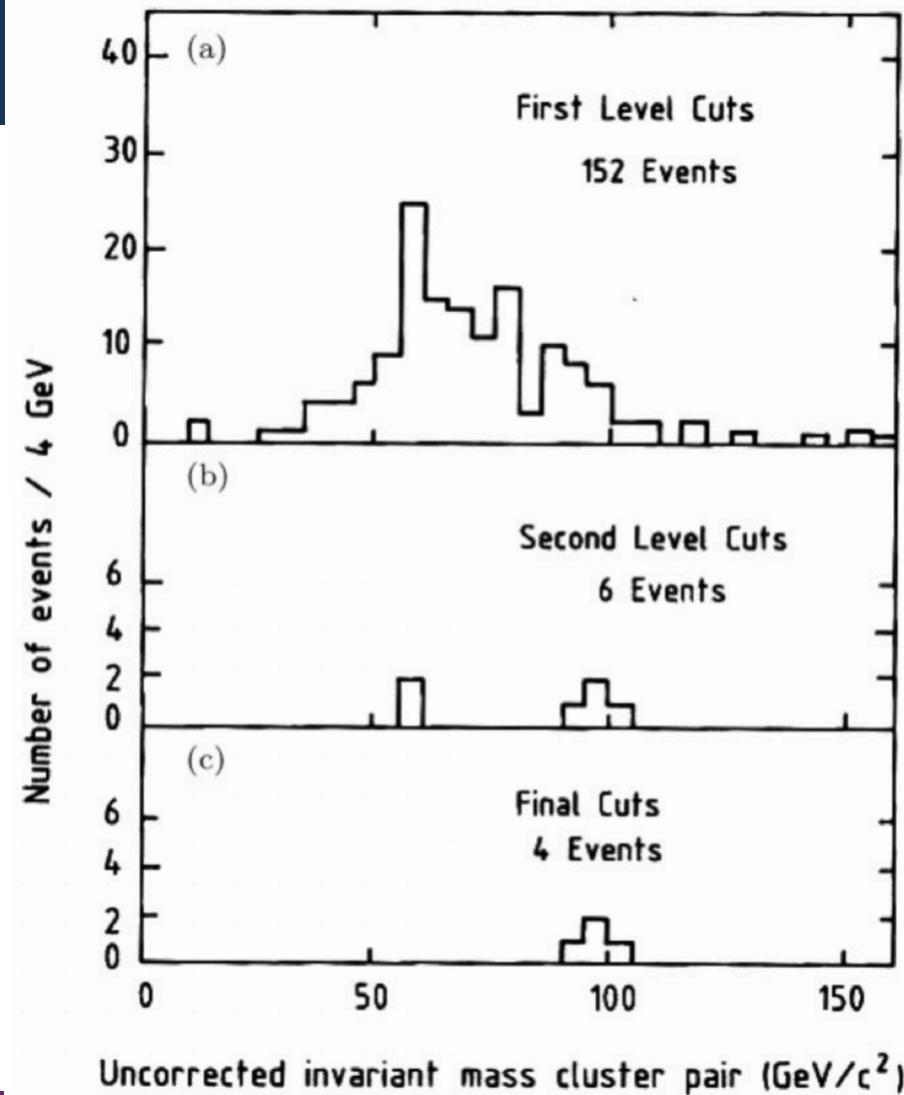
Yang-Mills Gleichungen

$$D_\mu F^{\mu\nu} = (\partial_\mu - igA_\mu) F^{\mu\nu} = 0$$

mit dem Feldstärketensor

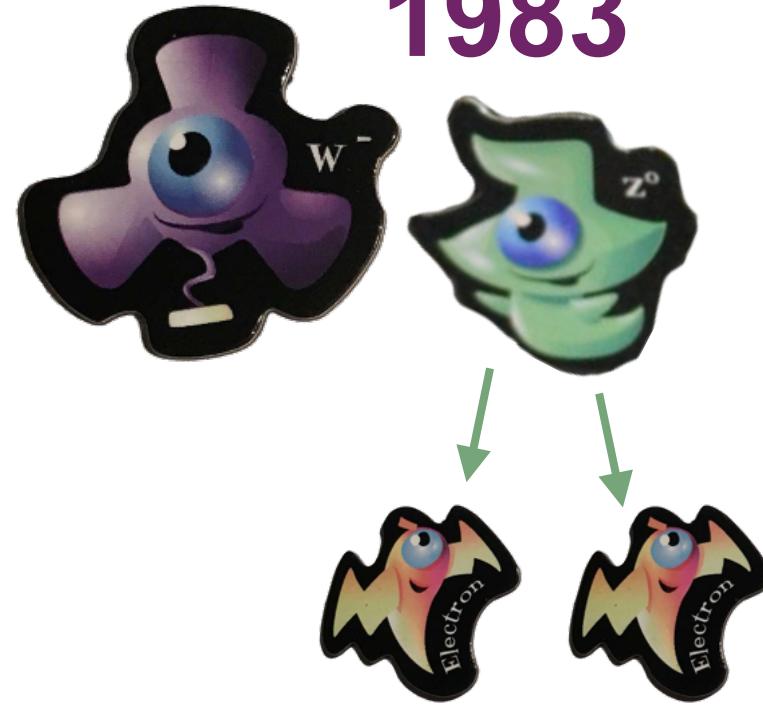
$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu + ig[A^\mu, A^\nu]$$

Teilchen die Kräfte übermitteln haben (eigentlich) keine Masse.



Entdeckung W/Z Boson

1983

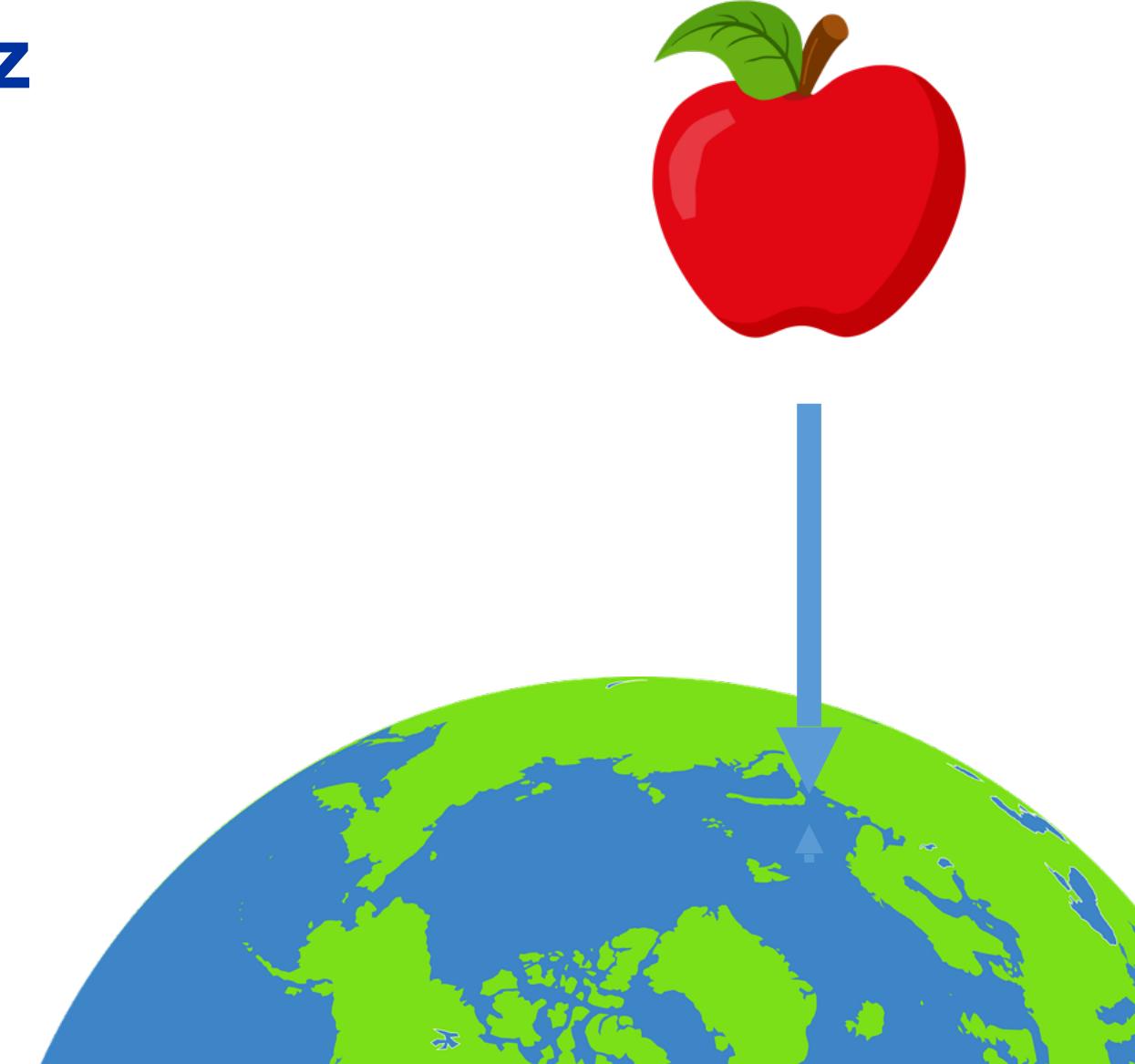


Experiment: W und Z Bosonen haben Masse.



Newtons Gravitationsgesetz

$$F = G \cdot m_1 \cdot m_2 / r^2$$



Newtons Gravitationsgesetz

$$F = G \cdot m_1 \cdot m_2 / r^2$$



Newtons Gravitationsgesetz

$$F = G \cdot m_1 \cdot m_2 / r^2$$



Experiment: Der Ballon steigt hoch!

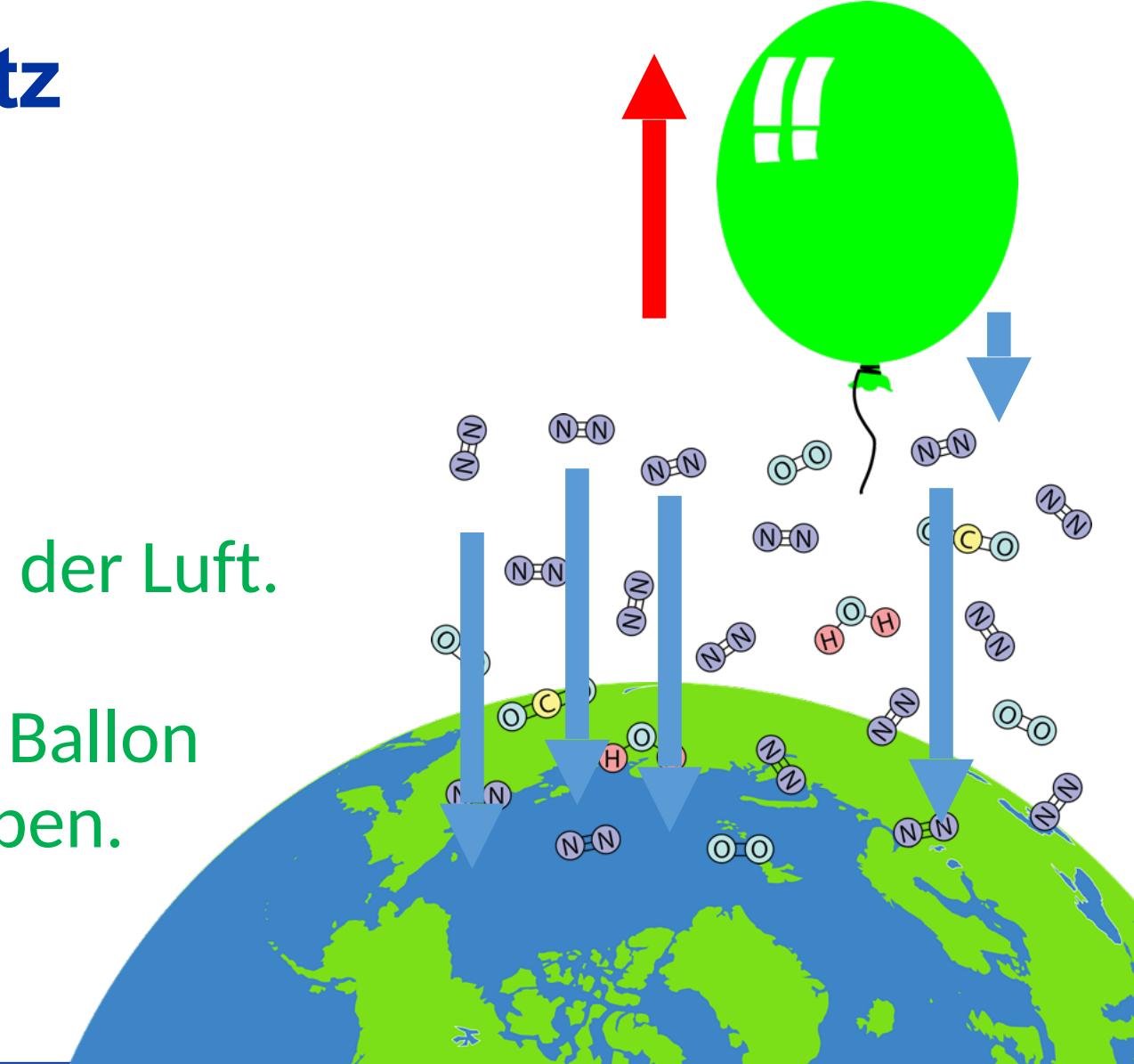
Entweder
Gravitationsgesetz falsch
oder der Ballon hat
negative Masse.



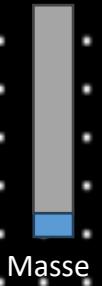
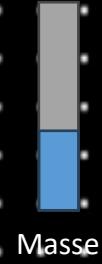
Newtons Gravitationsgesetz

Lösung: Der Ballon befindet sich in der Luft.

Helium ist leichter als Luft und der Ballon bewegt sich durch Auftrieb nach oben.



Higgs-Feld





Masse



Masse



Masse

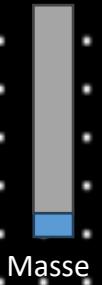
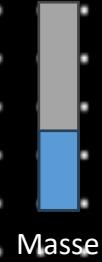


Masse



Masse

Higgs-Feld



BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

In a recent note¹ it was shown that the Goldstone theorem,² that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenome-

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction¹; by a gauge vector meson we mean a Yang-Mills field² associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.³ In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.⁴⁻⁶ A characteristic feature of such theories is the

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance.

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,[†] C. R. Hagen,[‡] and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

In all of the fairly numerous attempts to date to formulate a consistent field theory possessing a broken symmetry, Goldstone's remarkable theorem¹ has played an important role. This theorem, briefly stated, asserts that if there exists a conserved operator Q_i such that

$$[Q_i, A_j(x)] = \sum_k t_{ijk} A_k(x),$$

and if it is possible consistently to take $\sum_k t_{ijk} \times \langle 0 | A_k | 0 \rangle \neq 0$, then $A_j(x)$ has a zero-mass particle in its spectrum. It has more recently been observed that the assumed Lorentz invariance essential to the proof² may allow one the hope of avoiding such massless particles through the in-

roduction of vector gauge fields and the consequent breakdown of manifest covariance.³ This, of course, represents a departure from the assumptions of the theorem, and a limitation on its applicability which in no way reflects on the general validity of the proof.

In this note we shall show, within the framework of a simple soluble field theory, that it is possible consistently to break a symmetry (in the sense that $\sum_k t_{ijk} \langle 0 | A_k | 0 \rangle \neq 0$) without requiring that $A(x)$ excite a zero-mass particle. While this result might suggest a general procedure for the elimination of unwanted massless bosons, it will be seen that this has been accomplished by giving up the global conservation law usually

1964

Vorhersage vom Higgs



Standard Model
Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} i \gamma^\mu \partial_\mu \psi + \bar{\phi} \nabla_\mu \phi + h.c.$$

Standard Model

matter particles

1st gen.

2nd gen.

3rd gen.

Q
V
A
R
K

u
up

d
down

c
charm

s
strange

t
top

b
bottom

L
E
P
T
O
N

v_e
e neutrino

e
electron

v_μ
μ neutrino

μ
muon

v_τ
τ neutrino

τ
tau

gauge particles
Strong Force

g
g
g
g
g
g
g
g

gluon

Electro-Magnetic Force

γ
photon

Weak Force

W⁺
W⁻
Z

W bosons
Z boson

scalar particle
H
Higgs

Wandering the immeasurable
à l'infini



Auf der Suche nach den kleinsten Bausteinen



17.4 Hard-Scattering Processes in Hadron Collisions

$$\sigma(p(P_1) + p(P_2) \rightarrow Y + X)$$

$$= \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \rightarrow Y)$$

$$(i\gamma^\mu \partial_\mu - m)\psi = \begin{pmatrix} -m & i(\partial_0 + \boldsymbol{\sigma} \cdot \boldsymbol{\nabla}) \\ i(\partial_0 - \boldsymbol{\sigma} \cdot \boldsymbol{\nabla}) & -m \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} = 0.$$

$$\psi(x) = \int \frac{d^3 p}{(2\pi)^3} \frac{1}{\sqrt{2E_p}} \sum_s \left(a_p^s u^s(p) e^{-ip \cdot x} + b_p^{s\dagger} v^s(p) e^{ip \cdot x} \right);$$

$$\bar{\psi}(x) = \int \frac{d^3 p}{(2\pi)^3} \frac{1}{\sqrt{2E_p}} \sum_s \left(b_p^s \bar{v}^s(p) e^{-ip \cdot x} + a_p^{s\dagger} \bar{u}^s(p) e^{ip \cdot x} \right).$$

$$\begin{aligned} S_F(x-y) &= \int \frac{d^4 p}{(2\pi)^4} \frac{i(\not{p} + m)}{p^2 - m^2 + i\epsilon} e^{-ip \cdot (x-y)} \\ &= \begin{cases} \langle 0 | \psi(x) \bar{\psi}(y) | 0 \rangle & \text{for } x^0 > y^0 \text{ (close contour below)} \\ -\langle 0 | \bar{\psi}(y) \psi(x) | 0 \rangle & \text{for } x^0 < y^0 \text{ (close contour above)} \end{cases} \end{aligned}$$

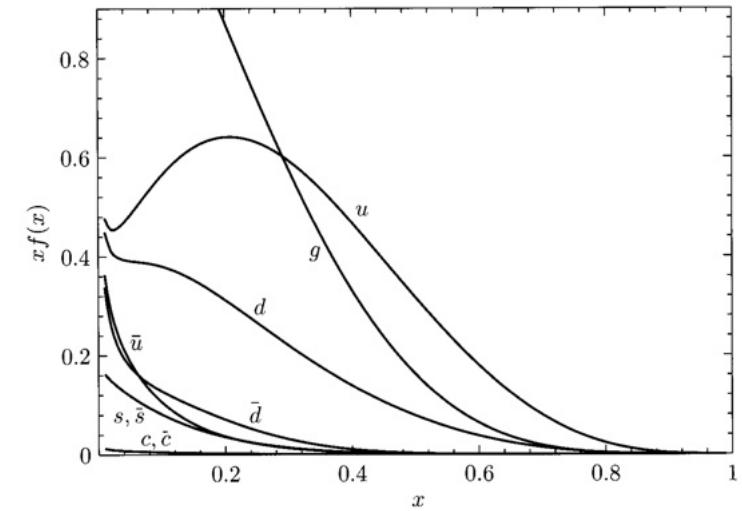
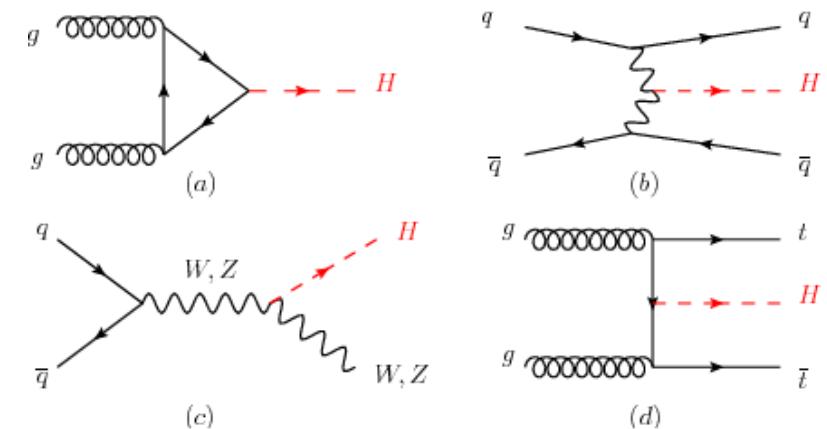


Figure 17.6. Parton distribution functions $x f_f(x)$ for quarks, antiquarks, and gluons in the proton, at $Q^2 = 4 \text{ GeV}^2$. These distributions are obtained from a fit to deep inelastic scattering data performed by the CTEQ collaboration (CTEQ2L), described in J. Botts, et. al., *Phys. Lett.* **B304**, 159 (1993).



$$E = mc^2$$

$E = mc^2$ 

$$E = mc^2$$





parishilton ✅
New York, New York

Follow



35k likes 1,937 comments

Love my lil #SupermodelPup! 😍聆听 Still trying to figure out the perfect name.
Deciding between #DiamondBaby or #LoveBug. Thoughts? 🤔

OCTOBER 12, 2016





Teilchenbeschleuniger

Rischart
Seit
1883



24/7 Onlineshop!



EDEN HOTEL WOLFF

HIB Brauhaus Tegernsee HIB

PETER & WOLFF





The Large Hadron Collider und über 4,5 Millionen weitere Bücher verfügbar für Amazon Kindle. Erfahren Sie mehr

« Zurück zu den Suchergebnissen für "large hadron collider"



ATLAS Experiment © 2016 CERN

The Large Hadron Collider

von [CERN](#)

17 Kundenrezensionen auf Amazon.com

Unverb. Preisempf.: EUR 3 000 000 000,00

Preis: **EUR 2 999 999 794,99** & GRATIS Lieferung innerhalb
Deutschlands

Sie sparen: **EUR 205,01 (0 %)**

Alle Preisangaben inkl. USt

Hinweis: Keine Versandvorteile für Prime-Mitglieder.

Since 2008 scientists have conducted experiments in a hyperenergized, 17-mile supercollider beneath the border of France and Switzerland. The Large Hadron Collider (or what scientists call "the LHC") is one of the wonders of the modern world--a highly sophisticated scientific instrument designed to recreate in miniature the conditions of the universe as they existed in the microseconds

▼ Mehr lesen

Teilen <Einbetten>

EUR 2 999 999 794,99

Alle Preisangaben inkl. USt

GRATIS Lieferung für Prime-Mitglieder

Gewöhnlich versandfertig in 1
bis 3 Wochen.

Warum warten? Entdecken Sie die
digitale Version und lesen Sie sofort
los auf jedem Gerät.

Verkauf und Versand durch Amazon.
Geschenkverpackung verfügbar.

Menge: ▾

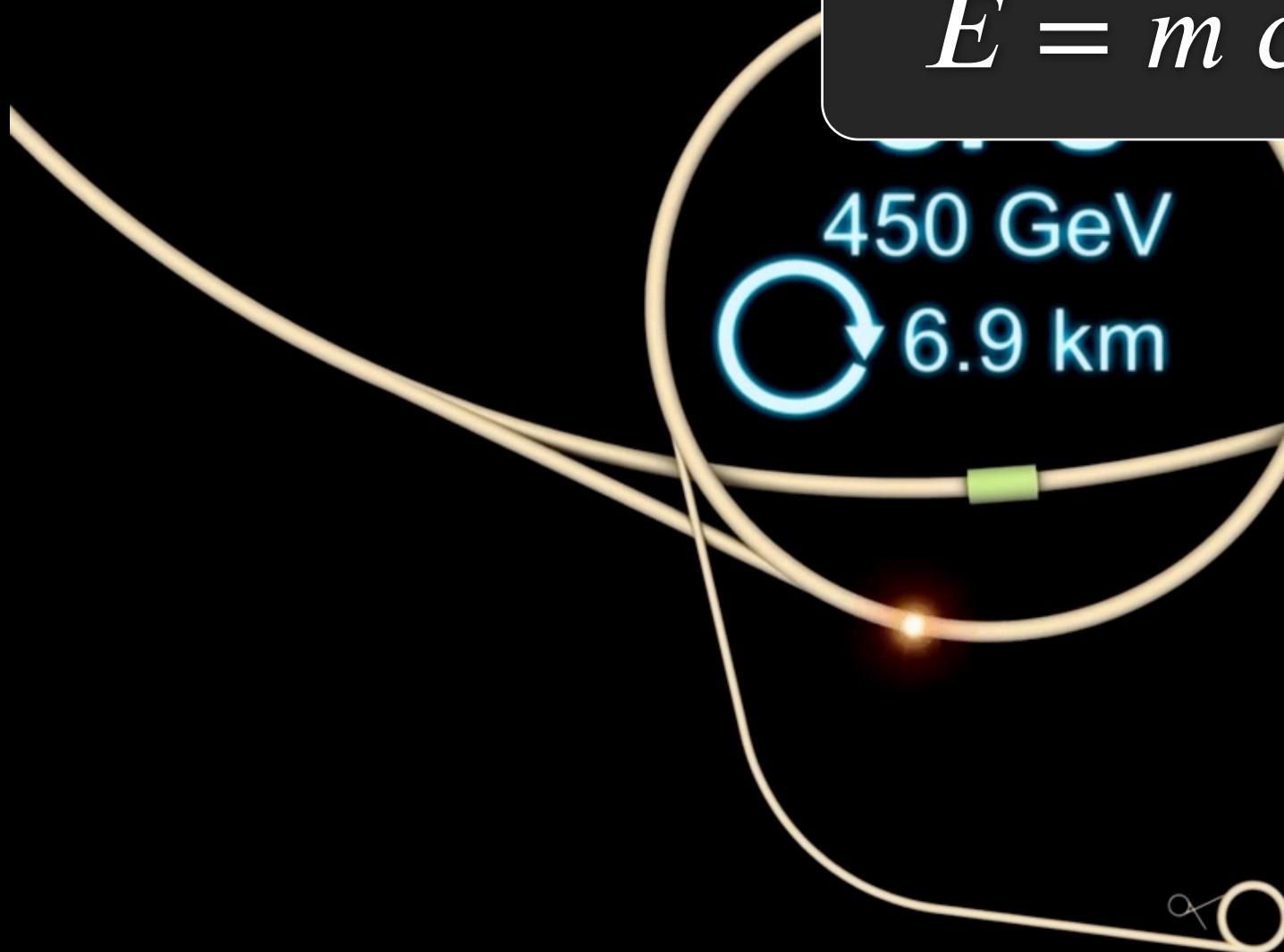
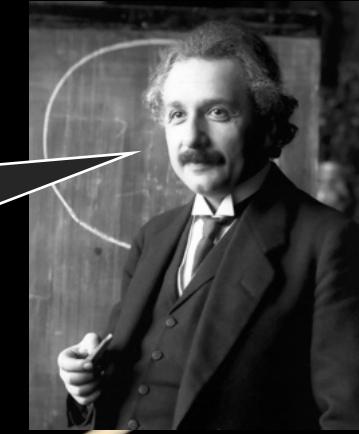


In den Einkaufswagen

Loggen Sie sich ein, um 1-Click®
einzuschalten.

$$E = m c^2$$

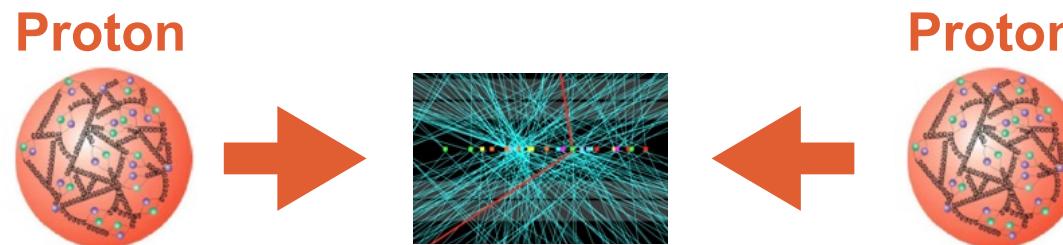
450 GeV
6.9 km



Large Hadron Collider – eine Entdeckungsmaschine

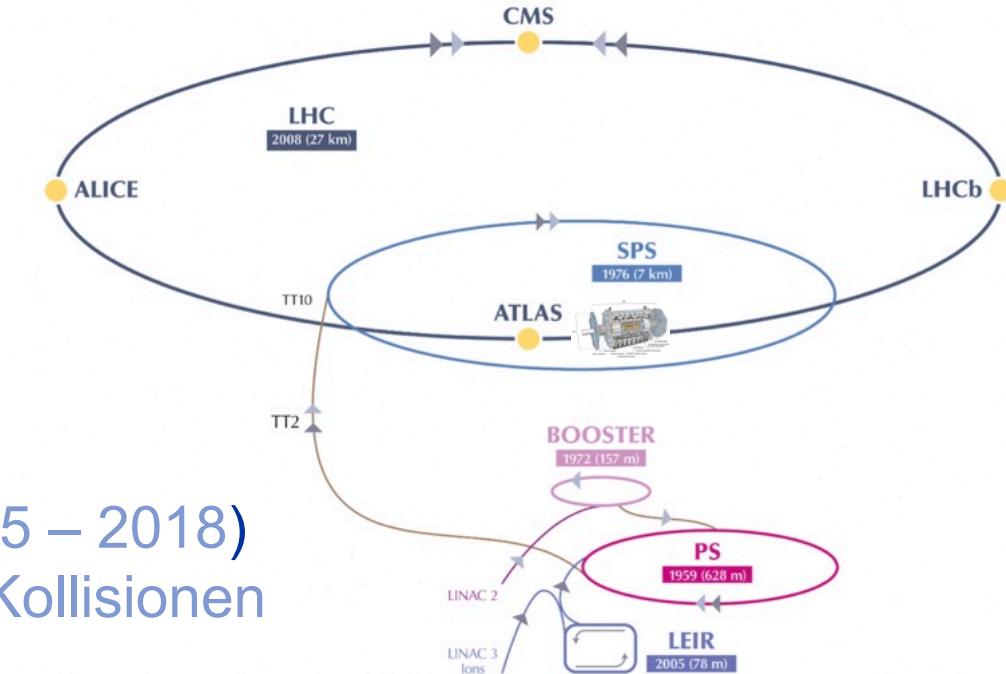
Hochenergetische (E) Teilchenkollisionen ermöglichen

- Untersuchung der Struktur der Materie (Auflösung $\sim 1/E$)
- Entdeckung neuer und massereicher Teilchen ($E = mc^2$)
- Untersuchung der Bedingungen im frühen Universum ($E = kT$)



Large Hadron Collider

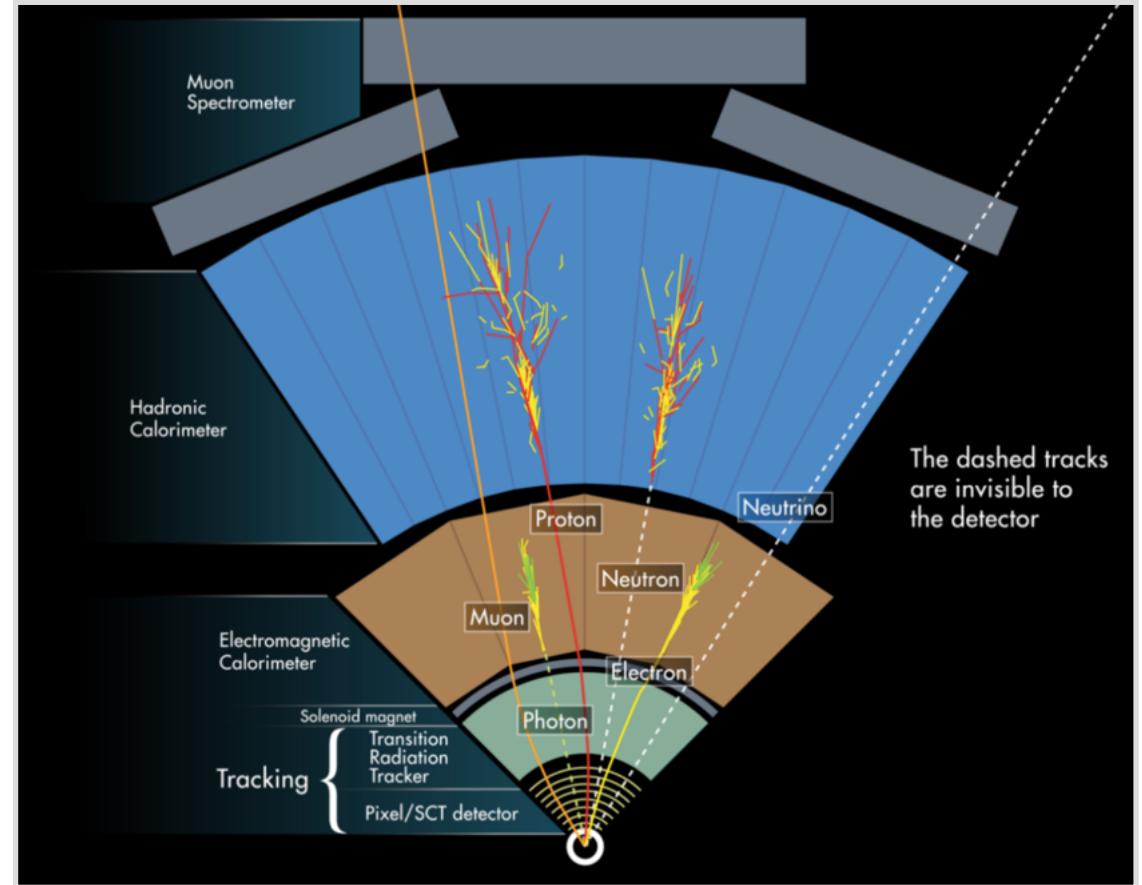
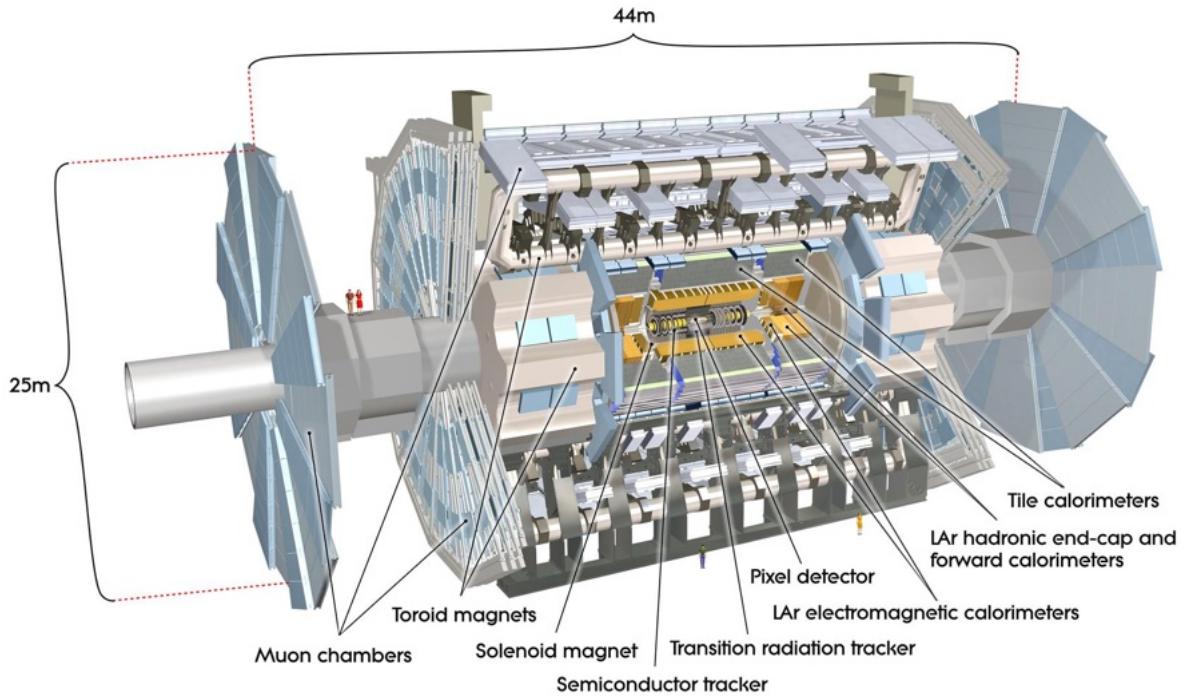
- Proton-Proton (pp) Kollisionen bei 13 TeV (Run 2, 2015 – 2018) und 13.6 TeV (Run 3, 2022 – 2025), auch pA und AA Kollisionen
- Vier große Experimente, heute Fokus auf ATLAS



ATLAS Experiment

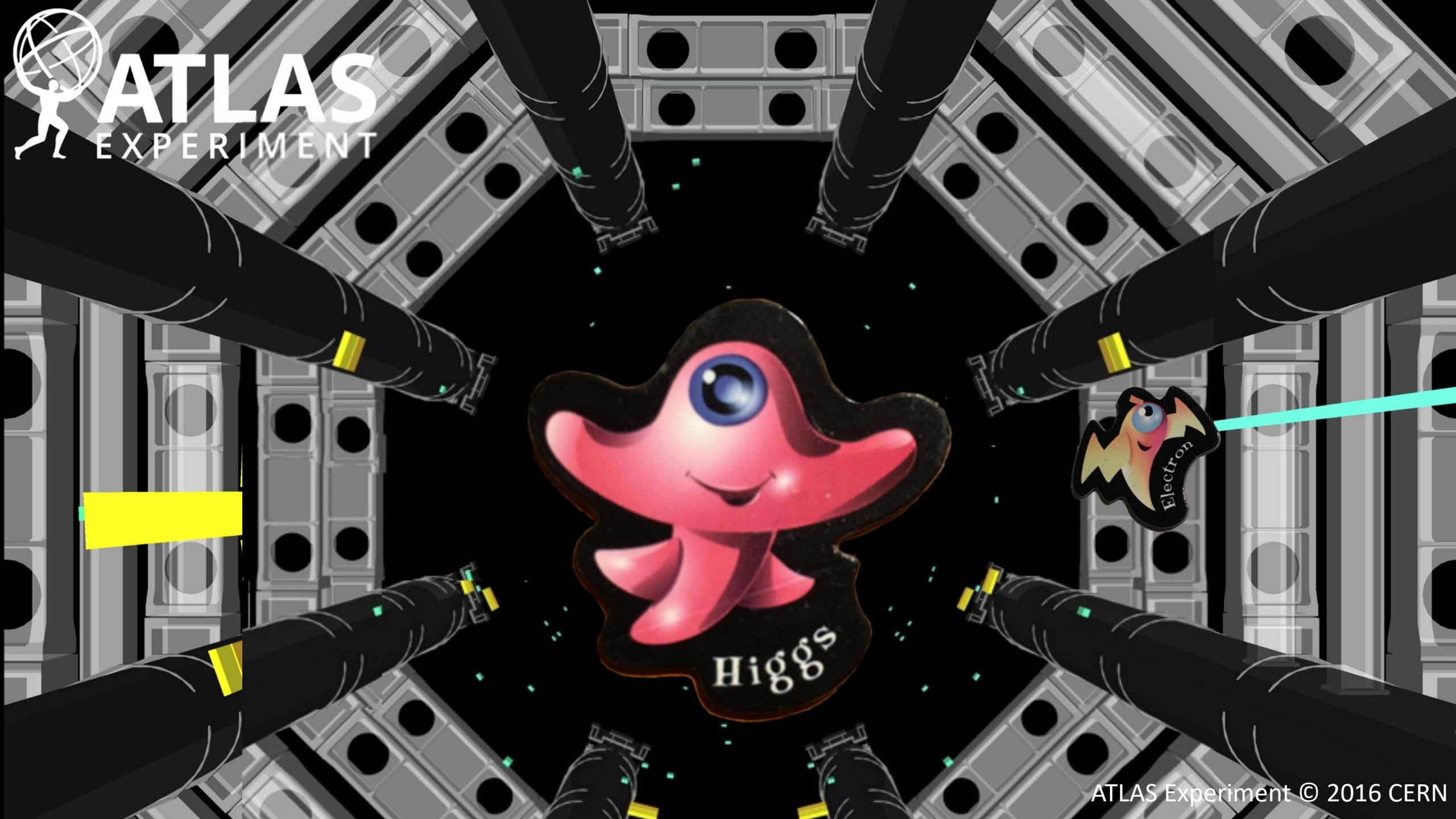
ATLAS Detektor

Vielzweck-Detektor zum Nachweis aller in Kollisionen erzeugter Teilchen als "3D-Fotos".



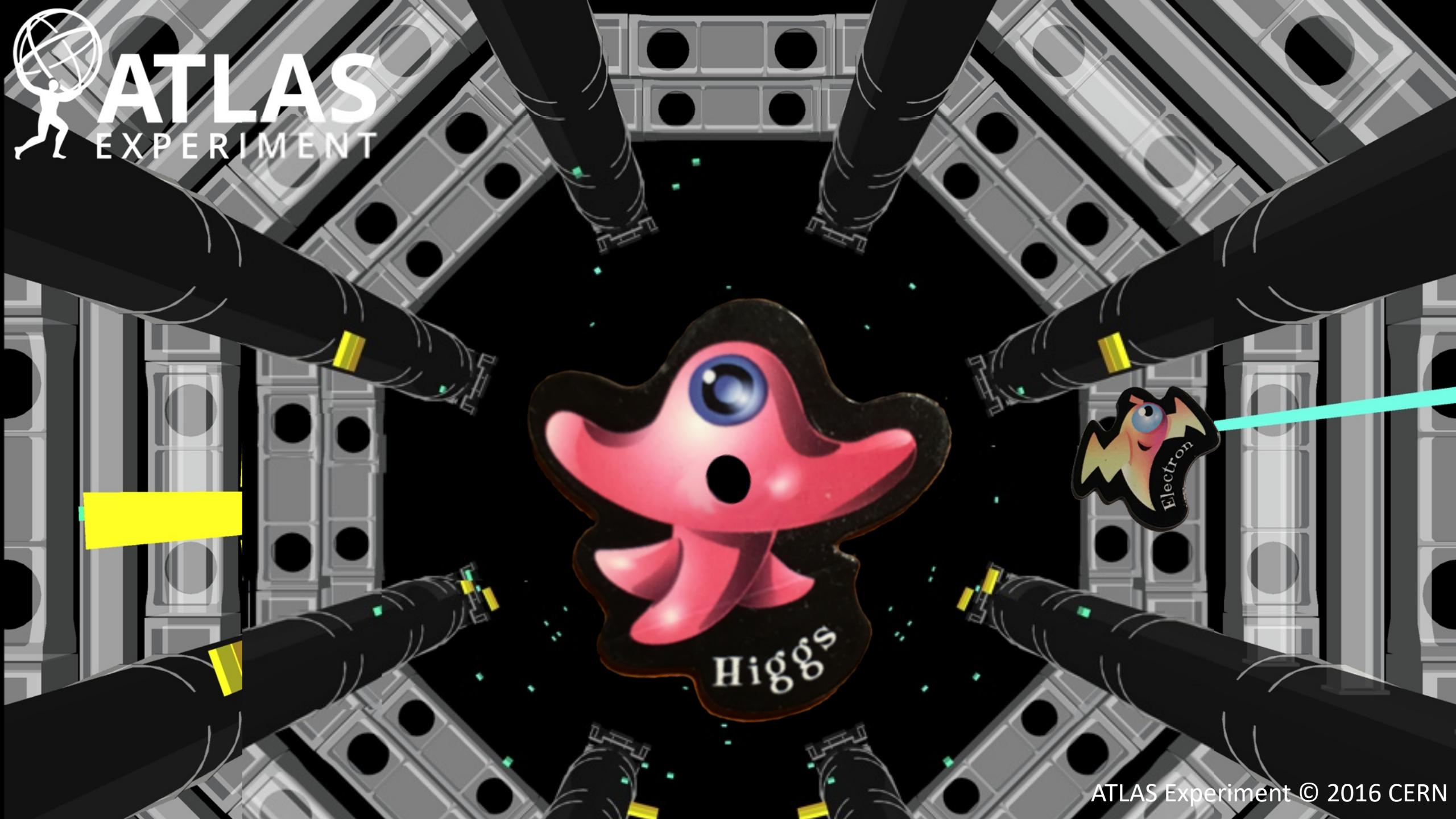


ATLAS
EXPERIMENT



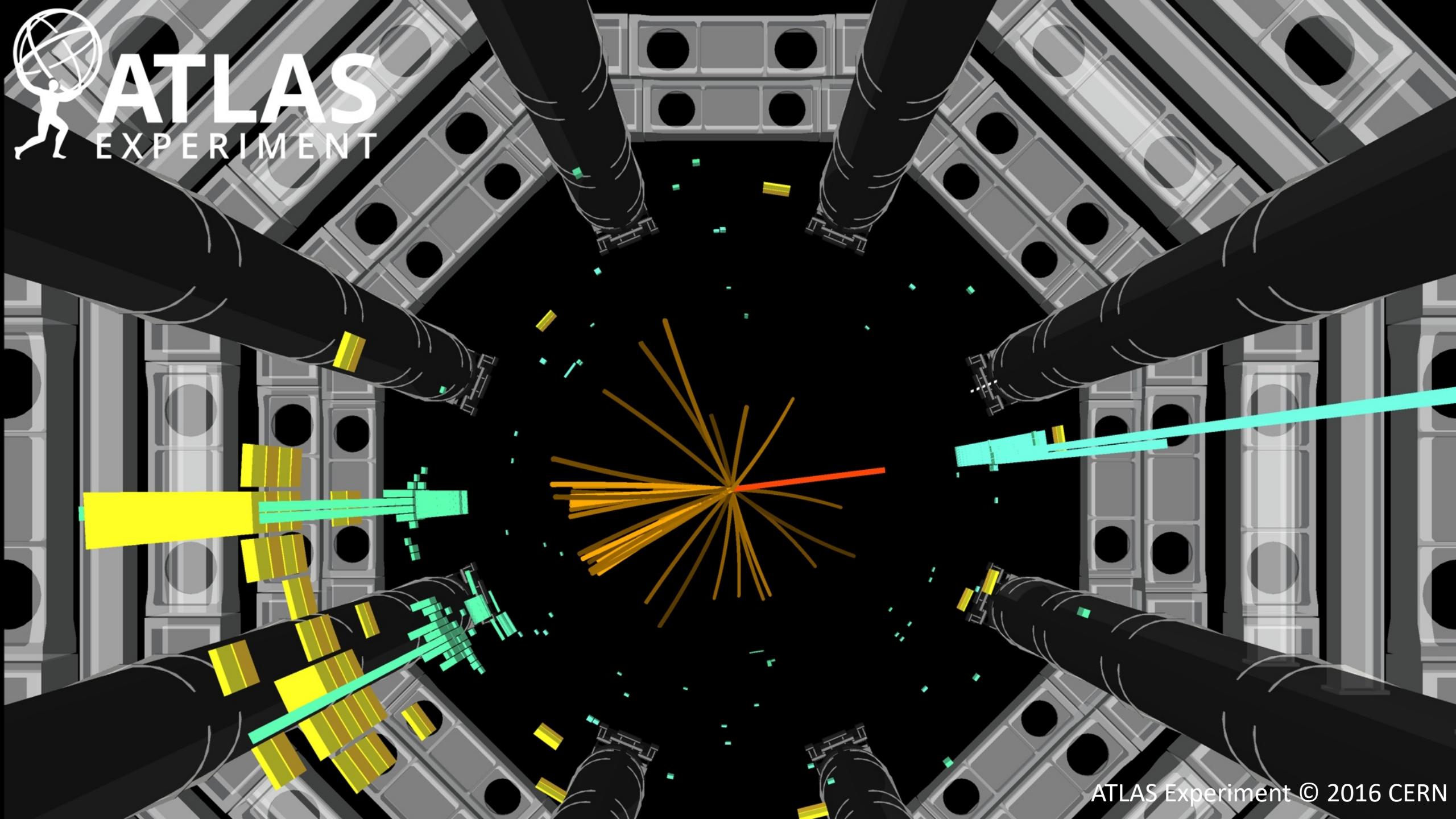


ATLAS
EXPERIMENT



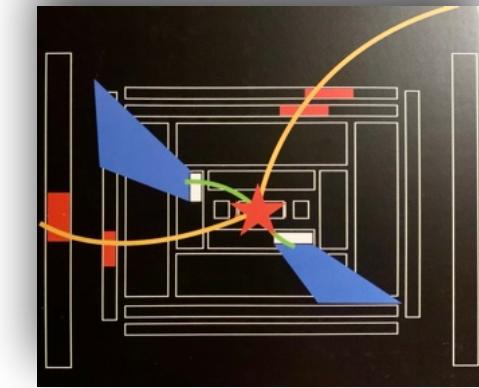


ATLAS
EXPERIMENT

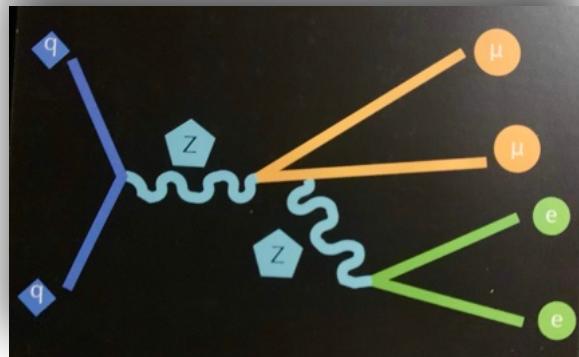


ATLAS Experiment © 2016 CERN

Daten- und Analyseprozess



Detektor

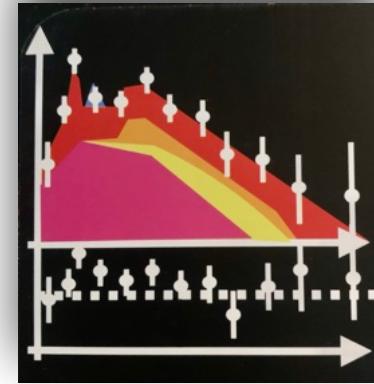


Theorie

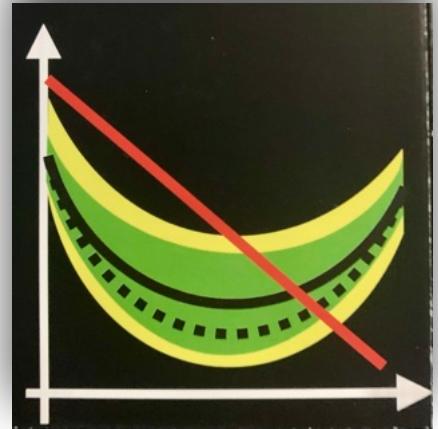
Selektion von
Kollisions-Ereignissen



"Digitaler Zwilling"
(Simulation)



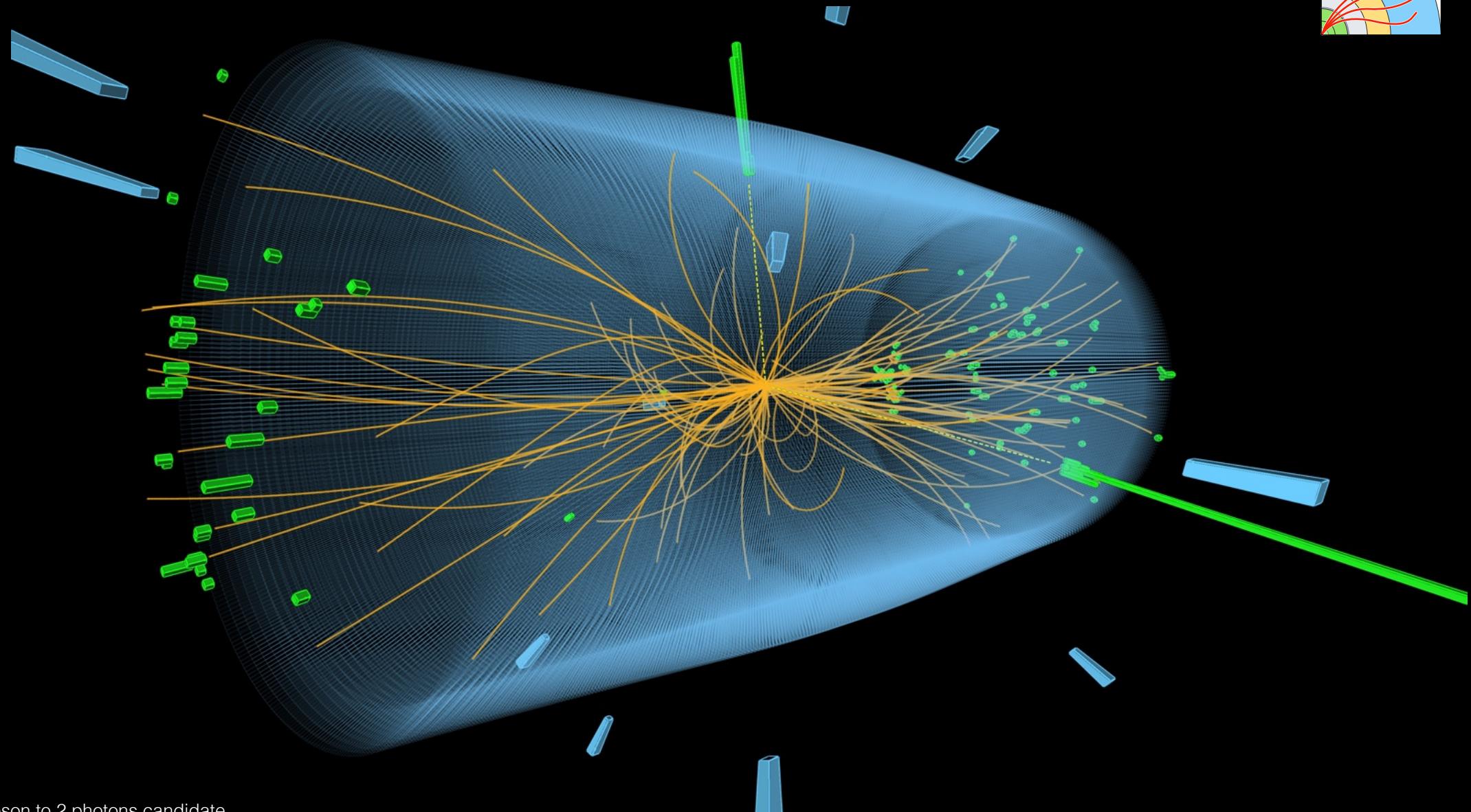
**Rekonstruktion &
Datenverdichtung**



**Statistische
Auswertung**

Source: "Particle Physics for Babies", L. Corpe

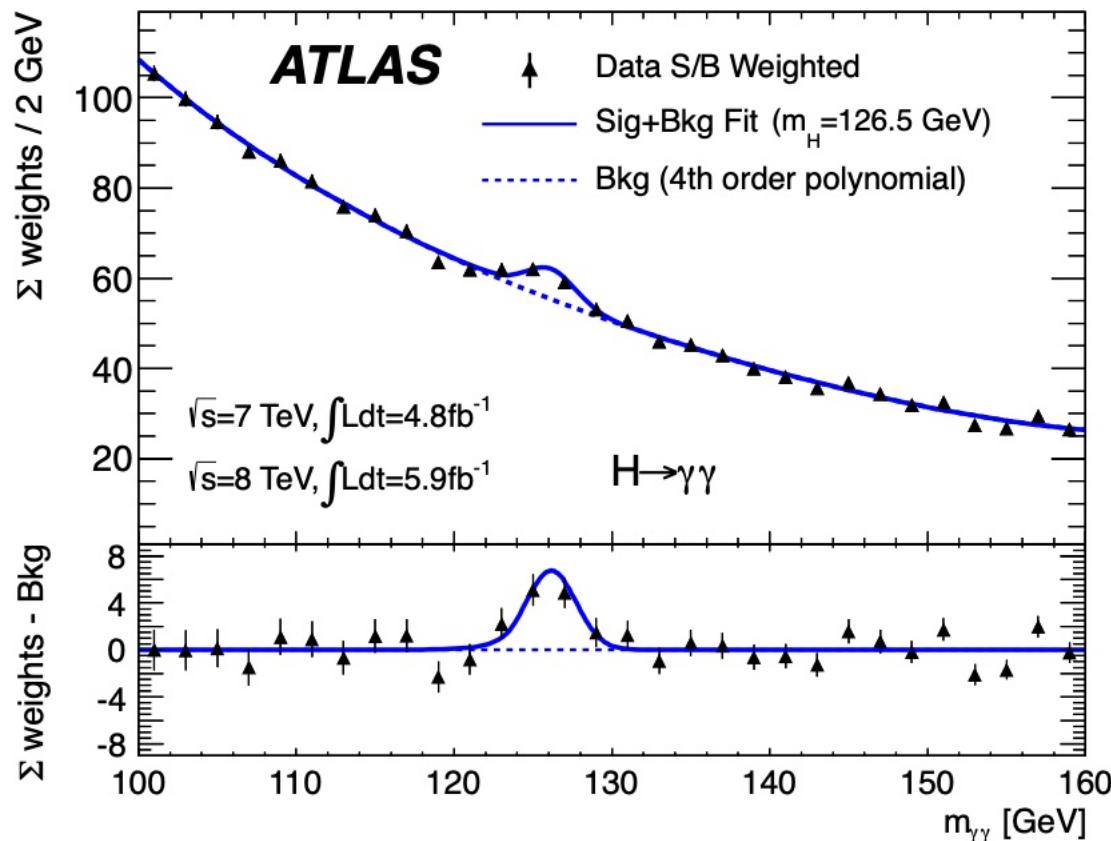
Higgs-Boson Entdeckung



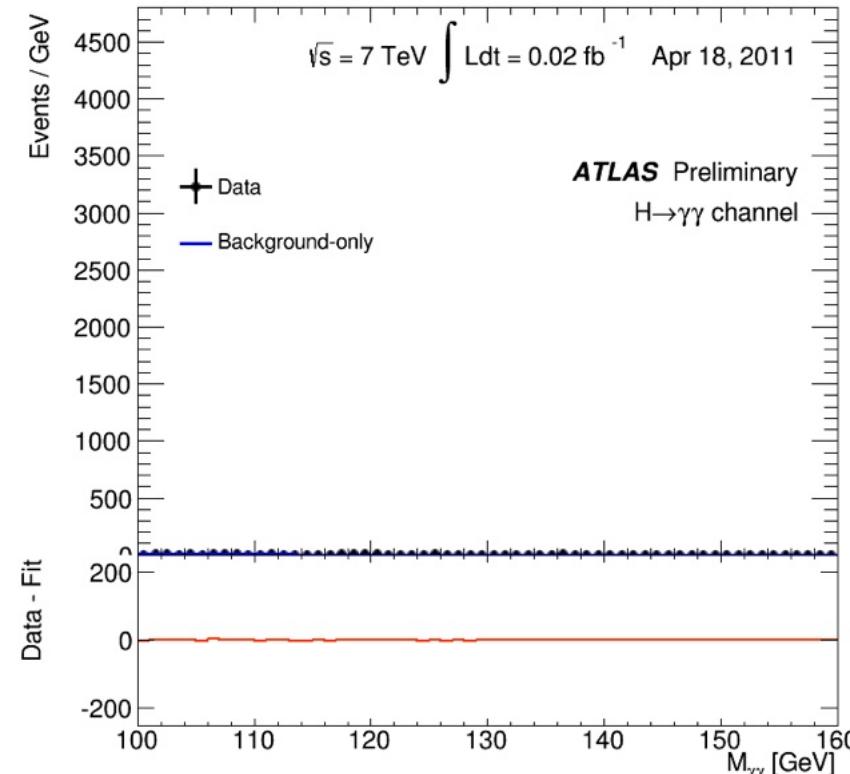
A Higgs boson to 2 photons candidate

Higgs-Boson Entdeckung

2012

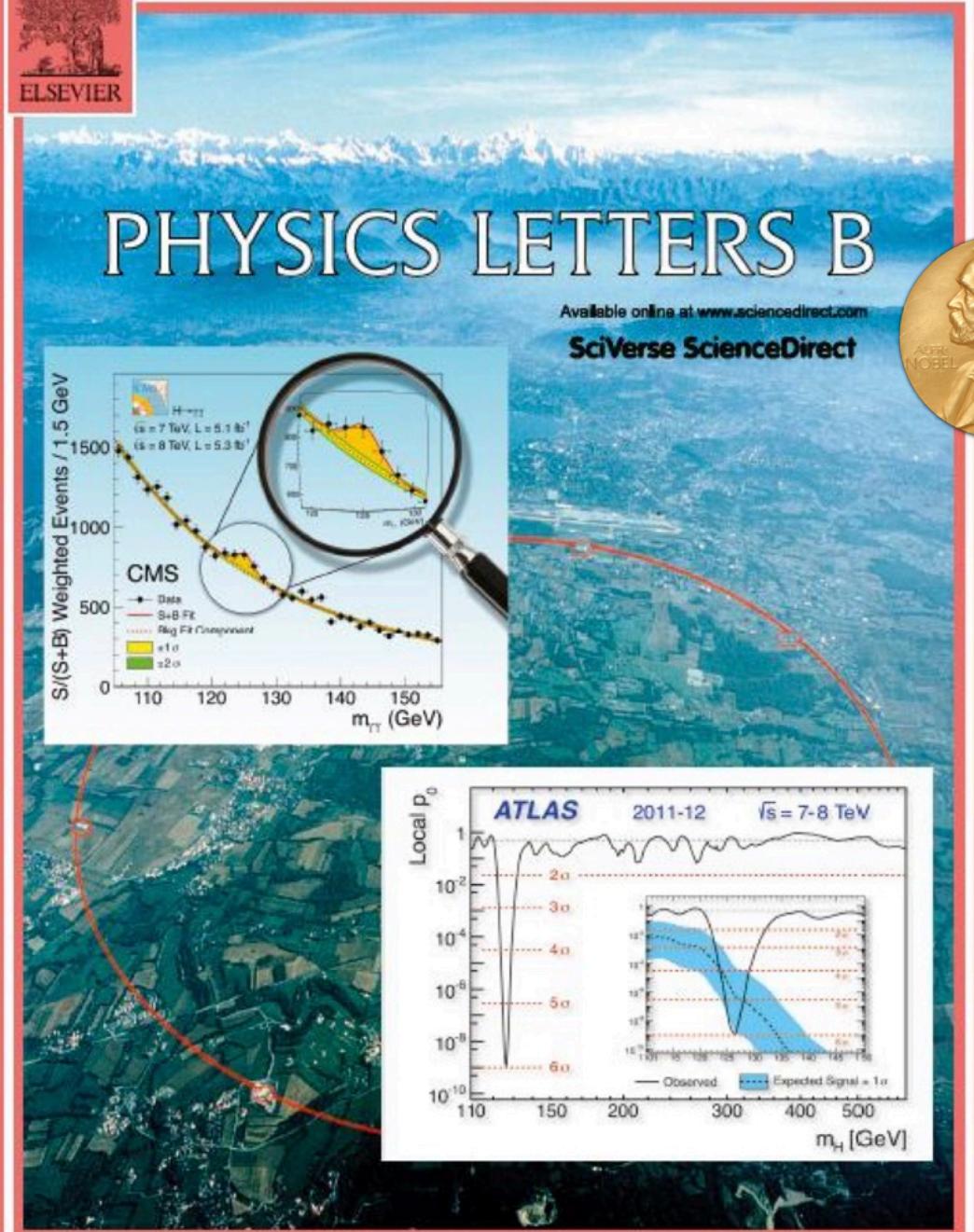
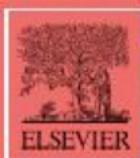


[Phys. Lett. B 716 \(2012\) 1-29](#)



A Higgs boson to 2 photons candidate





Higgs-Boson Entdeckung

04. Juli 2012

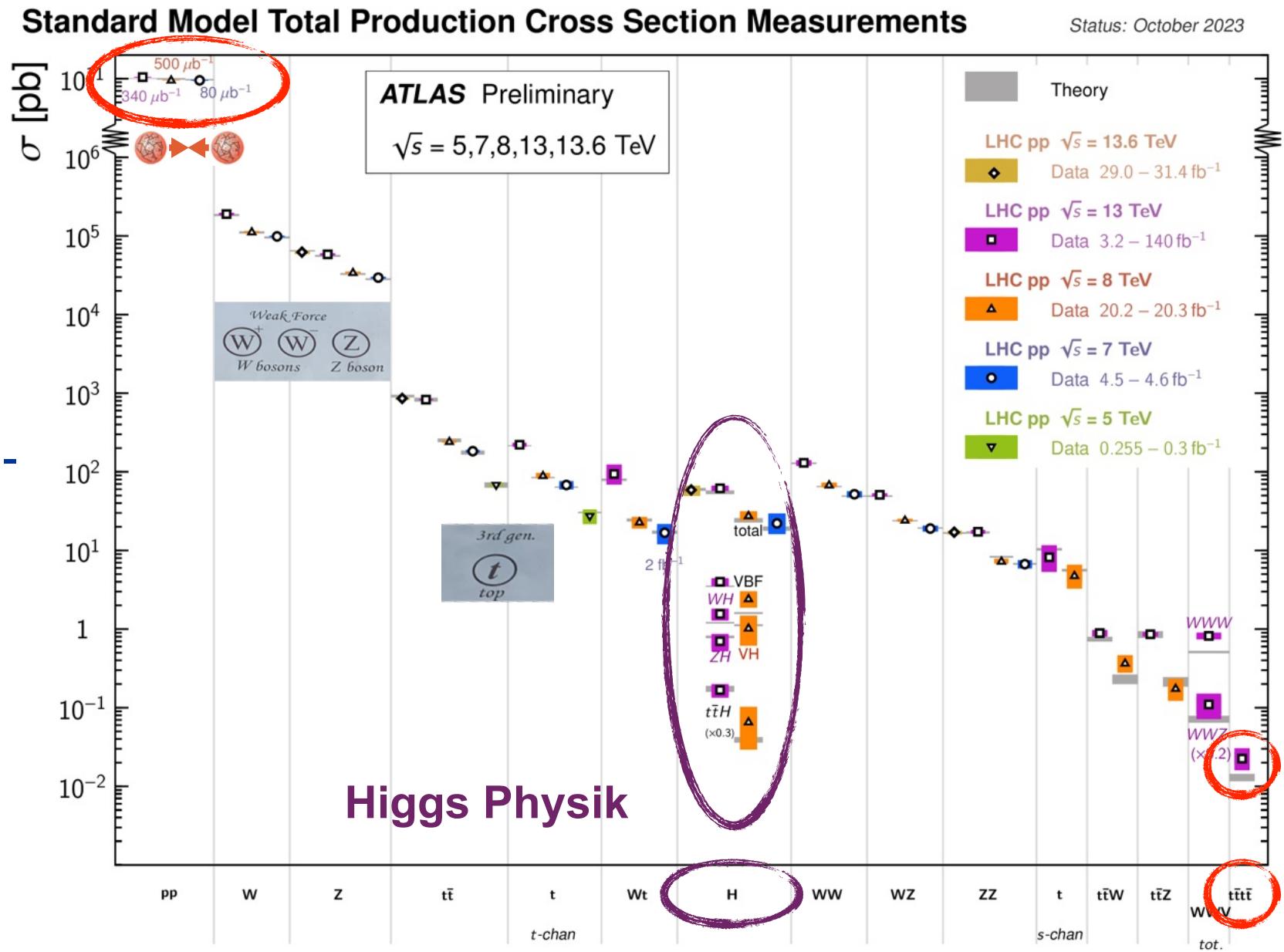


Physik Nobelpreis 2013



Messungen des Standard-Modells mit ATLAS

- Standardmodell anhand vieler Messungen mit Eich-Bosonen, Top-Quarks und anderen Teilchen über viele Größenordnungen bestätigt.
- Erste systematische Erkundung des Higgs-Feldes an Teilchenbeschleunigern.



Offene Fragen

Warum ist das Higgs Boson so leicht?

Gibt es neue Teilchen in der Nähe der Masse des Higgs-Bosons?

Ist das Higgs-Boson elementar oder zusammengesetzt?

Gibt es Anomalien in dessen Kopplung an die W- oder Z-Bosonen?

Was ist der Ursprung der enormen Bandbreite der Quark- und Leptonmassen?

Welche Rolle spielte das Higgs-Feld im frühen Universum?

Gibt es Anomalien in der Selbstkopplung des Higgs-Bosons?

Gibt es ladungs-paritätsverletzende Zerfälle des Higgs-Bosons?

Hat das Higgs-Boson eine Verbindung zu Dunkler Materie oder kosmischer Inflation?

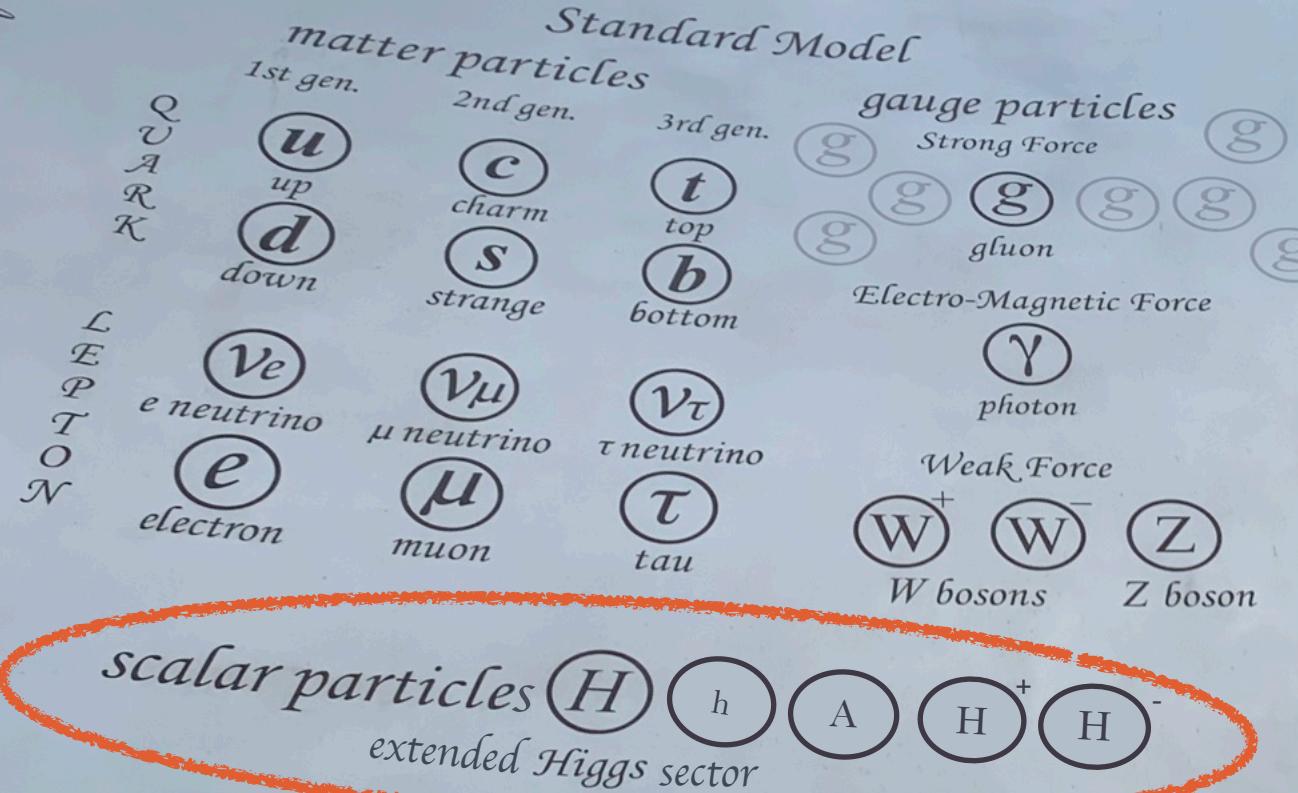


Standard Model Lagrangian

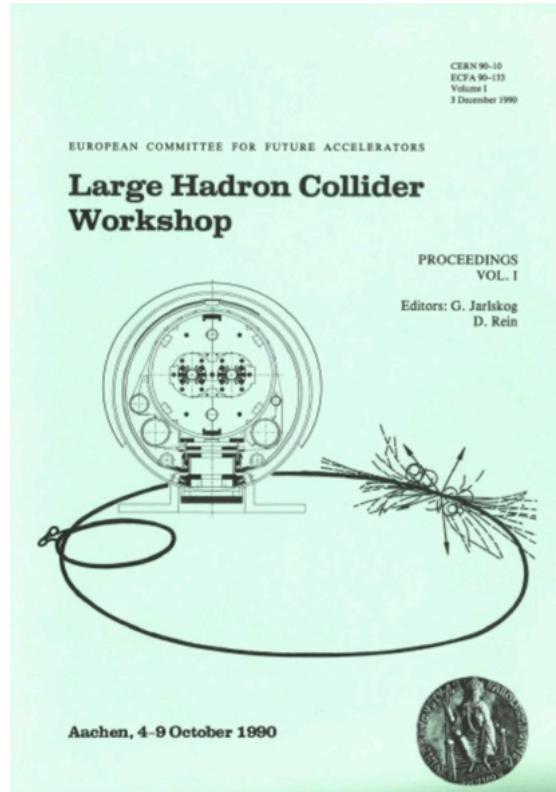
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} i \gamma^\mu \partial_\mu \psi + \bar{\chi}_i \gamma^\mu \partial_\mu \chi_i + \frac{1}{2} D_\mu \phi^2 - V(\phi) + h.c.$$

Beyond the
Standard Model
(BSM)?

Gibt es weitere Higgs-Bosonen?



WIE KOMMT MAN ZUR ARBEIT AM LARGE HADRON COLLIDER?



AM 04.10. IN AACHEN
(CERN - ECFA)
LARGE HADRON
COLLIDER
WORKSHOP

1990

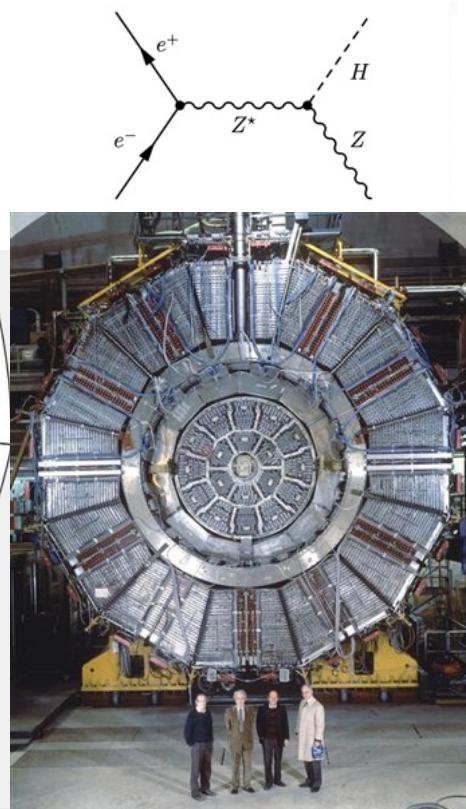
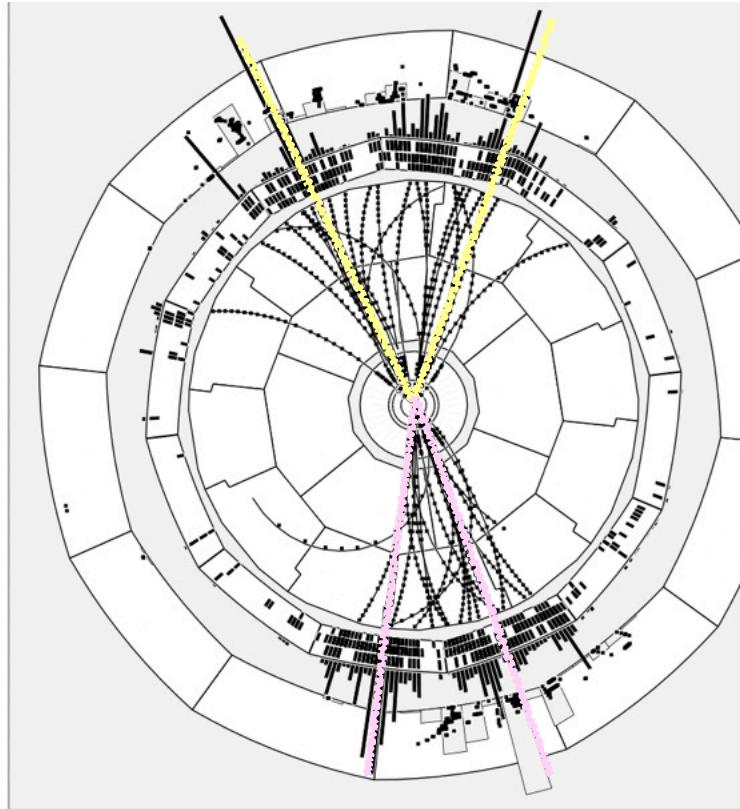


AM 01.01. IN
SCHLESWIG WERDE
ICH GEBOREN



HIGGS-BOSON-SUCHEN AM CERN MIT LEP

(LARGE ELECTRON-POSITRON COLLIDER)



Higgs-Boson-Kandidat mit
rekonstruierter Masse
113 GeV im Aleph-Detektor

von

1996

GRUNDSCHULE



ERSTE KOLLISIONEN IM LARGE HADRON COLLIDER



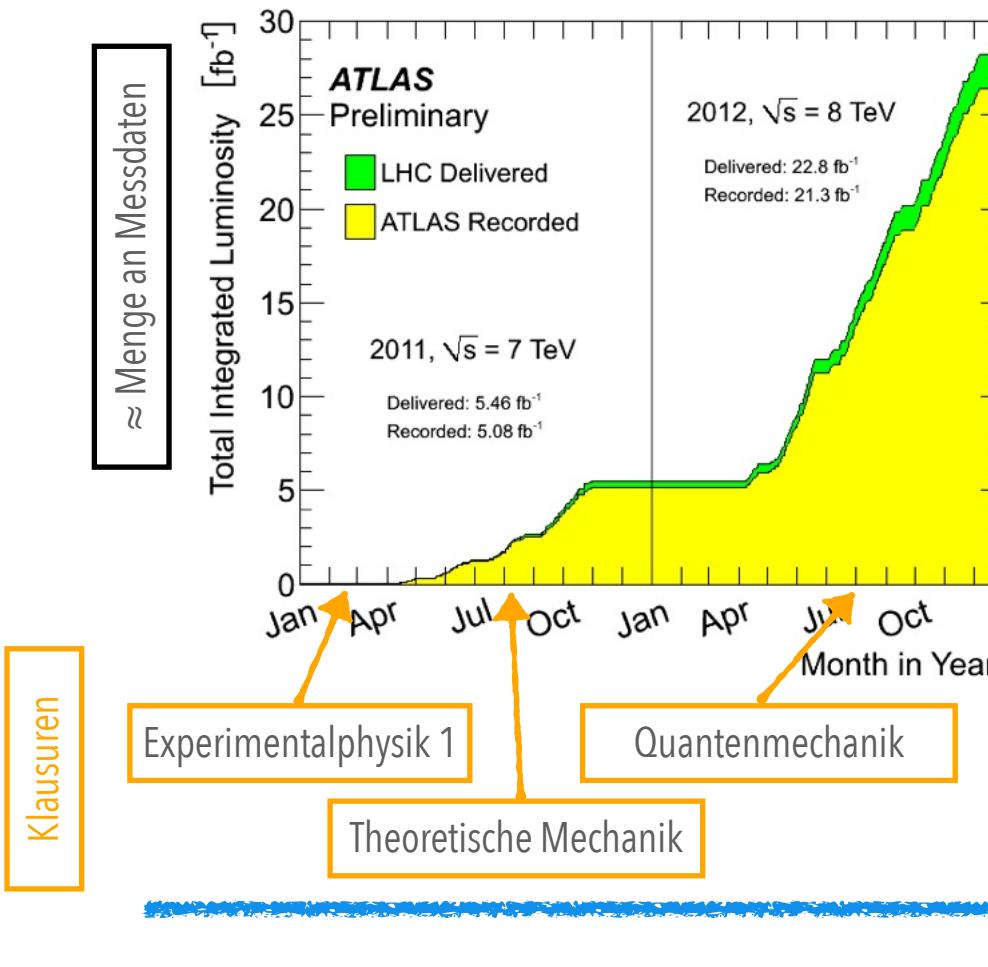
ABITUR (MOTTO:
"ABI POST")

2009



ERFOLGREICHE DATENNAHME AM LHC

PHYSIKSTUDIUM AN DER TU MÜNCHEN

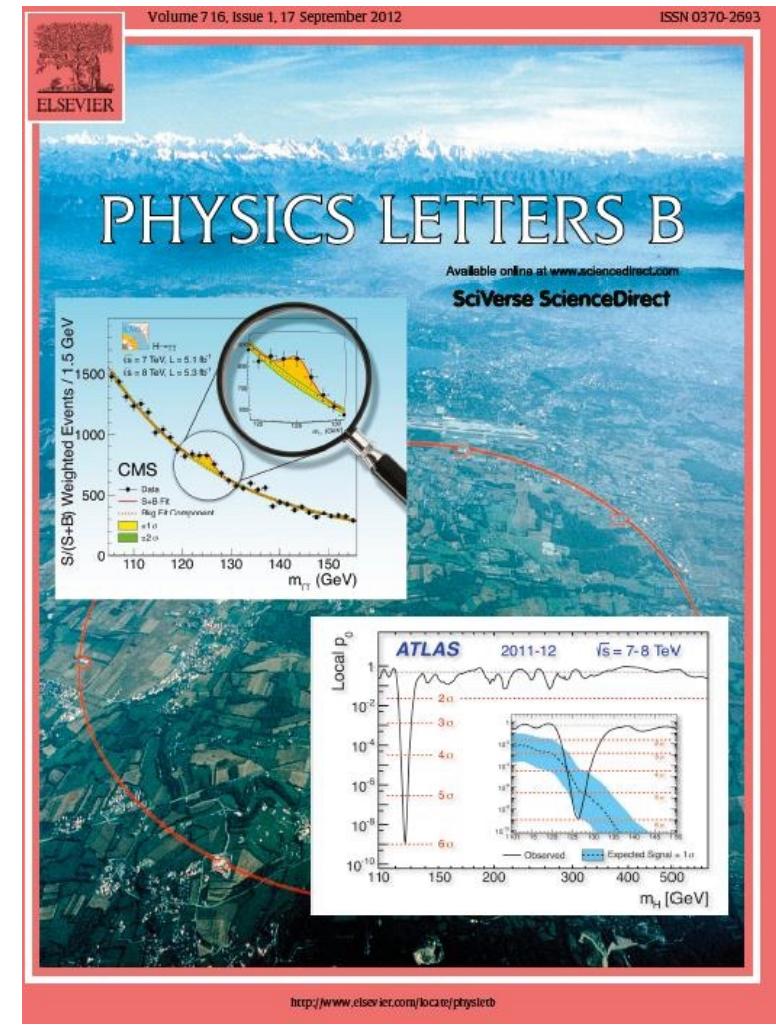


2010

ATLAS + CMS ENTDECKEN EIN "MIT DEM HIGGS-BOSON KONSISTENTES TEILCHEN"



2012



NOBELPREIS FÜR ENGLERT UND HIGGS



Higgs Hullabaloo



Physics Society University of Edinburgh ↵ « » ...
<edinburghphysicssociety@gmail.com>

An: [REDACTED]

Mo, 14.10.2013 20:40

Hi guys,

Hopefully you have all heard by now that we have a nobel laureate amongst us at Edinburgh! And in order to celebrate this properly we will be hosting a pub crawl tomorrow night. Come along to Teviot at 7:30 to enjoy a night of festivities and merriment.

AUSLANDSSEMESTER
EDINBURGH

2013



DOKTORAND AM MAX-PLANCK-INSTITUT FÜR PHYSIK



2016









Universum





$5 \times 10^{52} \text{ kg}$

ADE

TARE

Kg/L

ON/OFF

max:5kg,d=1g









Viel zu wenig!

$1 \times 10^{52} \text{ kg}$



ADE
germany

TARE

Kg/Lb

oz/lb

max:5kg,d=1g



Bekannte Materie



Bekannte Materie



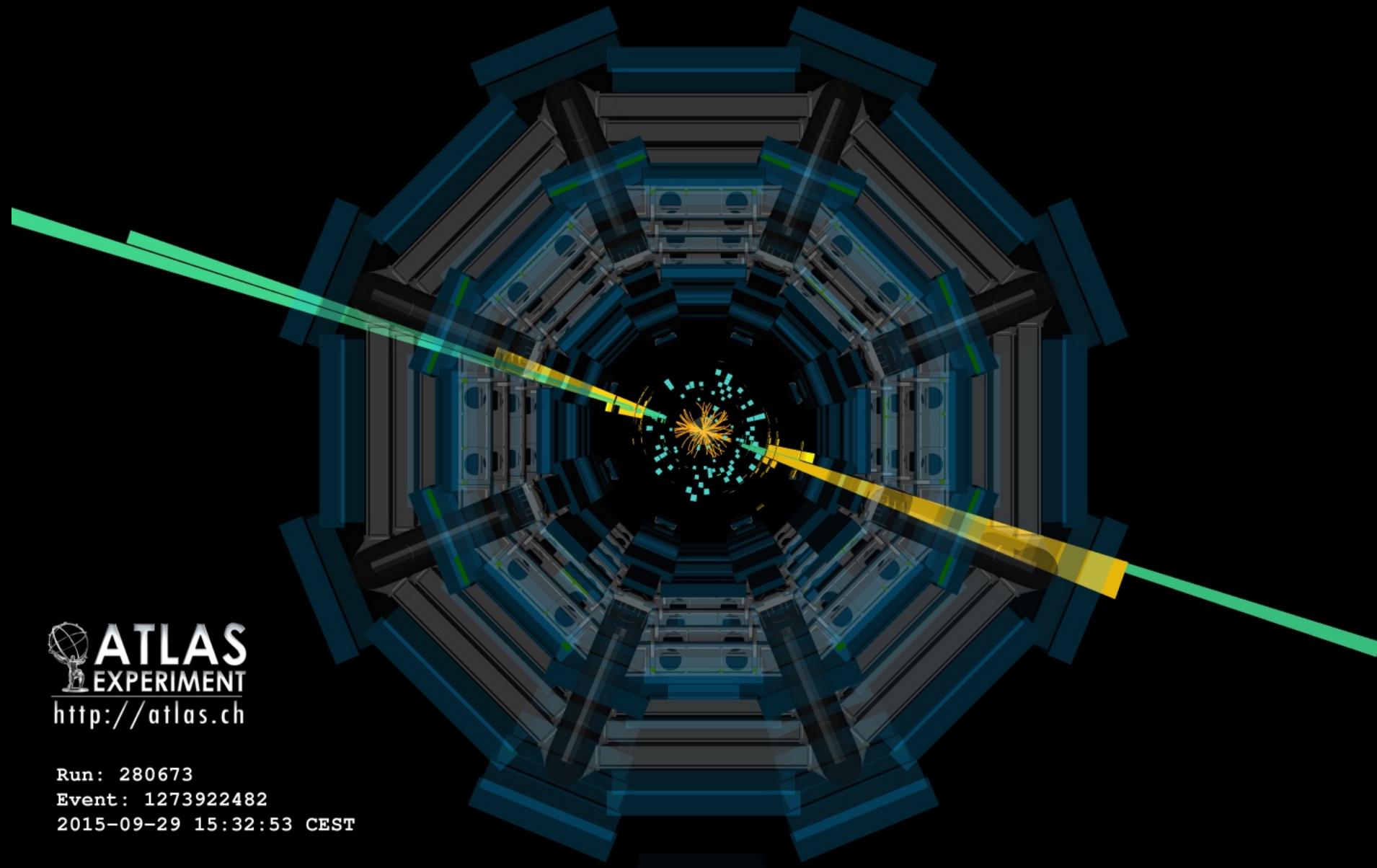
Dunkle Materie





Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST

ATLAS Experiment © 2016 CERN



© Peter Bohacek ISD 197
Direct Measurement Video





ATLAS
EXPERIMENT

entgegengesetzt



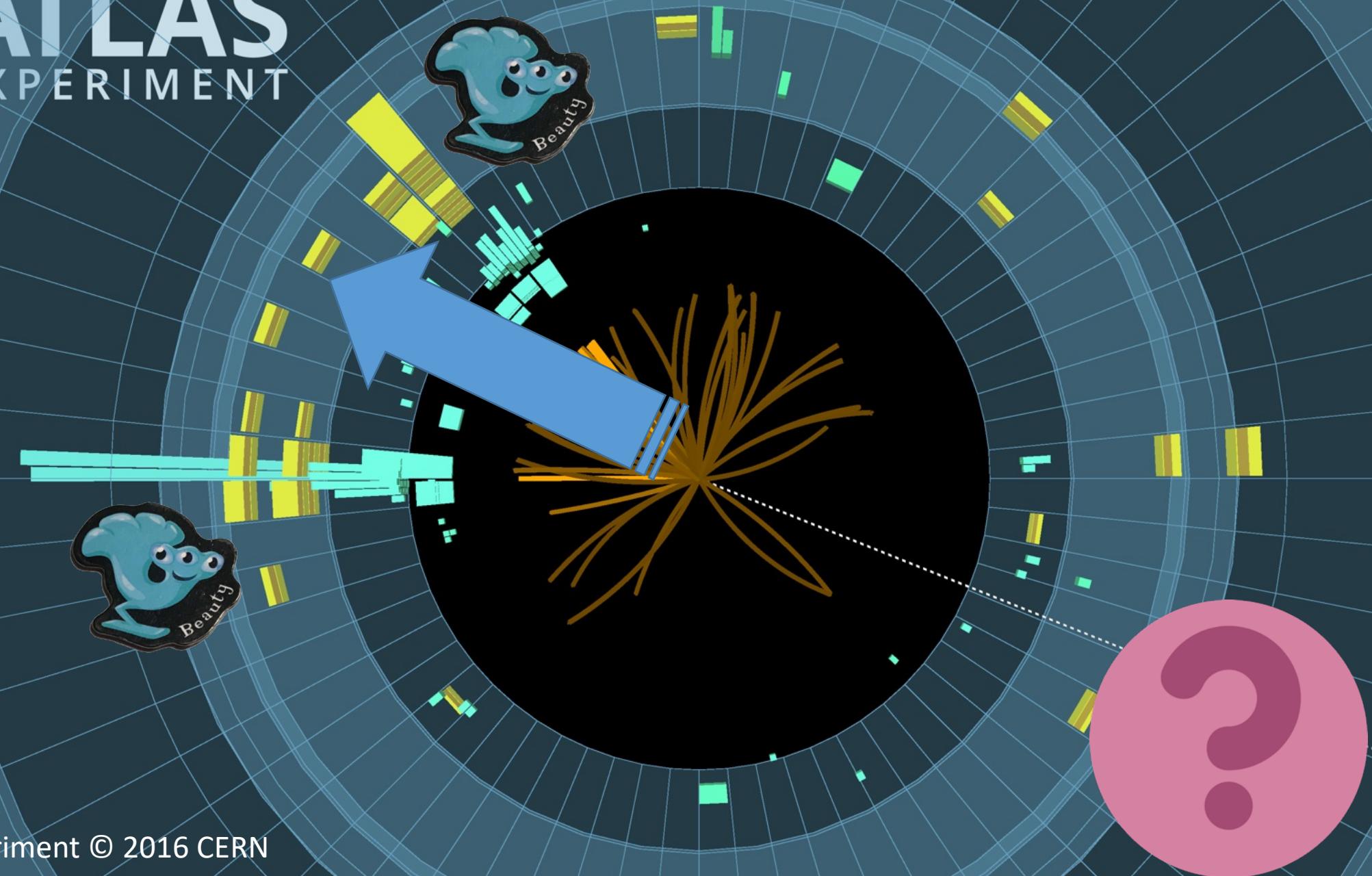
Beauty



Electron

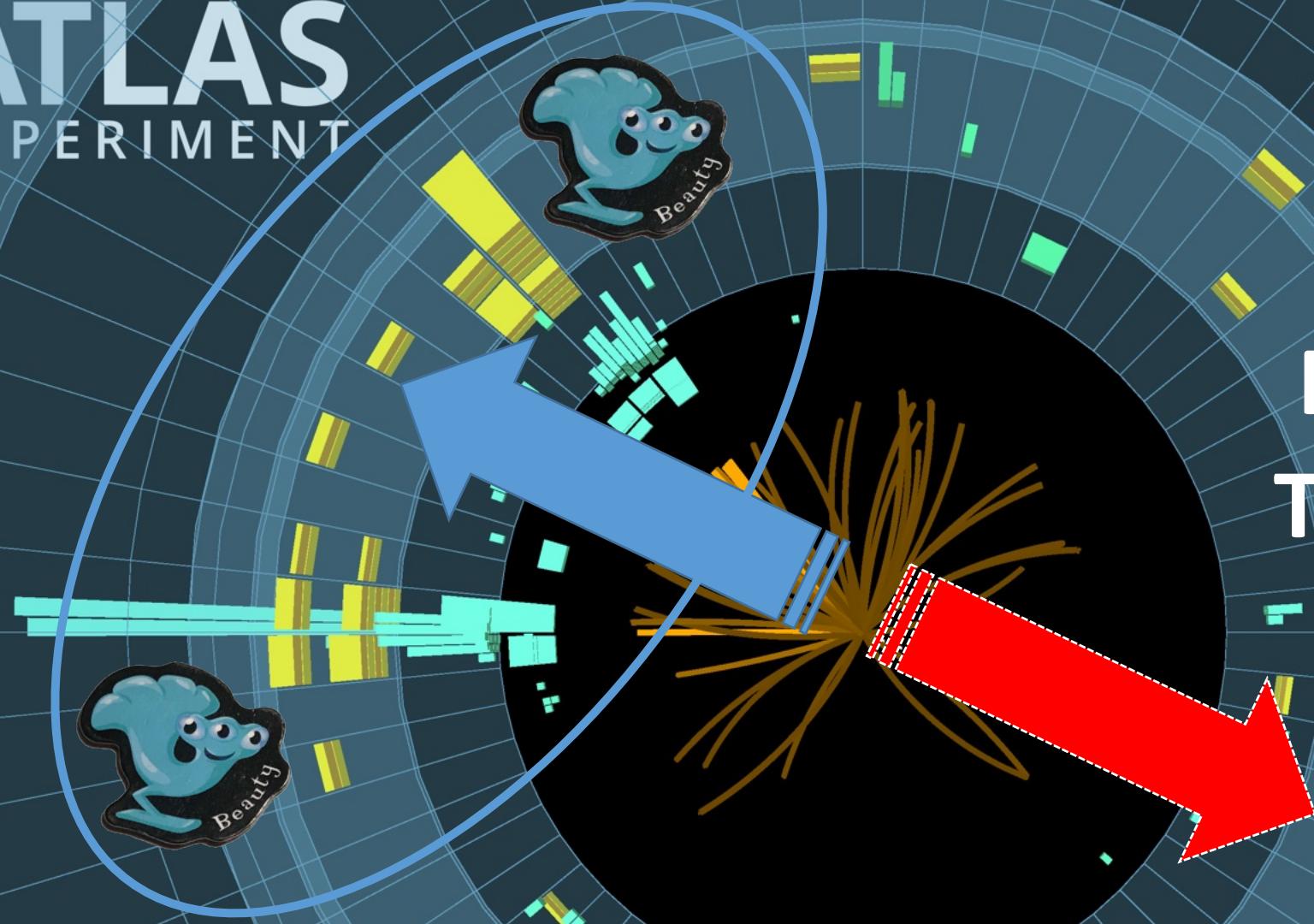


ATLAS
EXPERIMENT





ATLAS
EXPERIMENT



Fehlender
Transversal
impuls

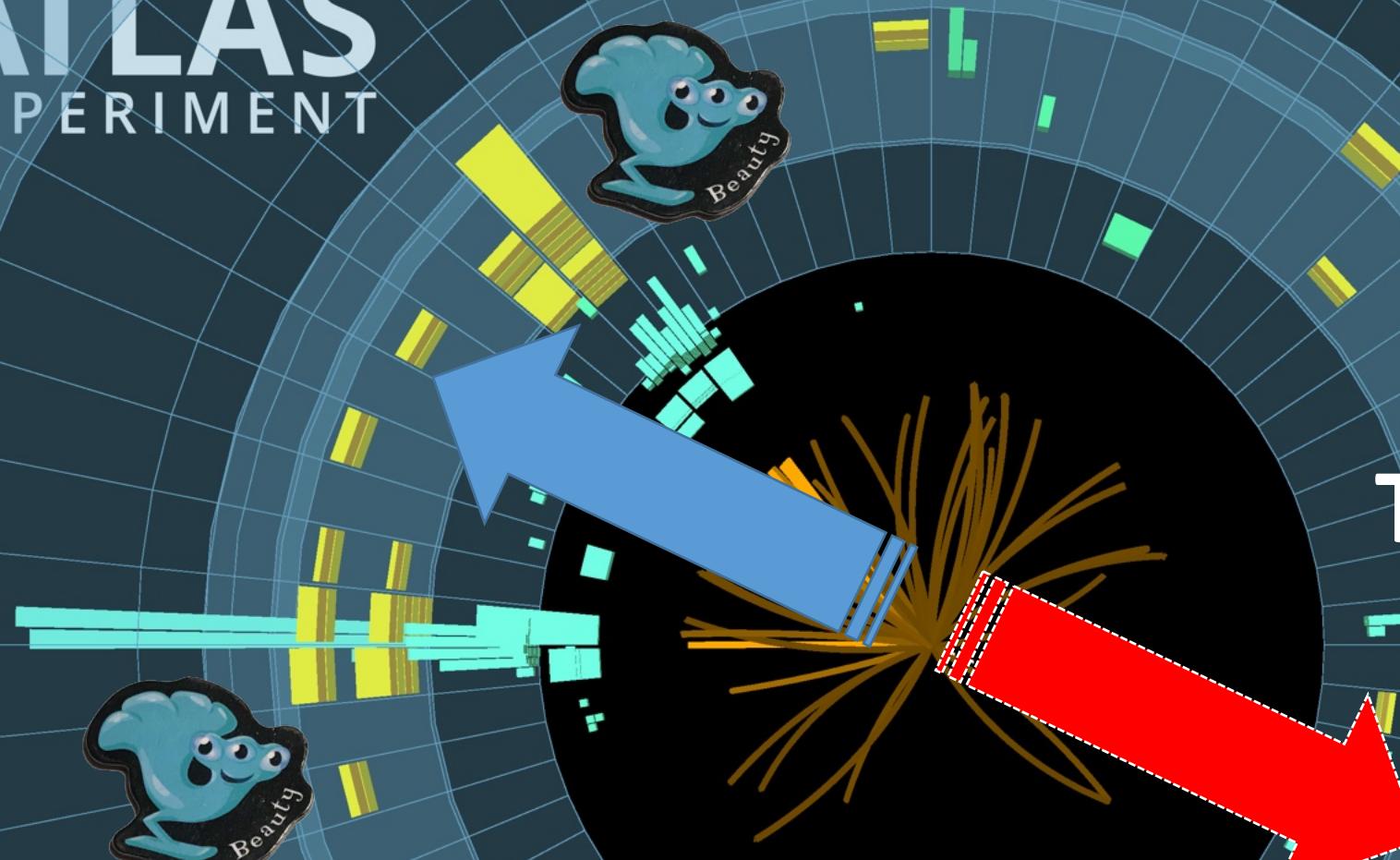


Higgs-Boson





ATLAS
EXPERIMENT

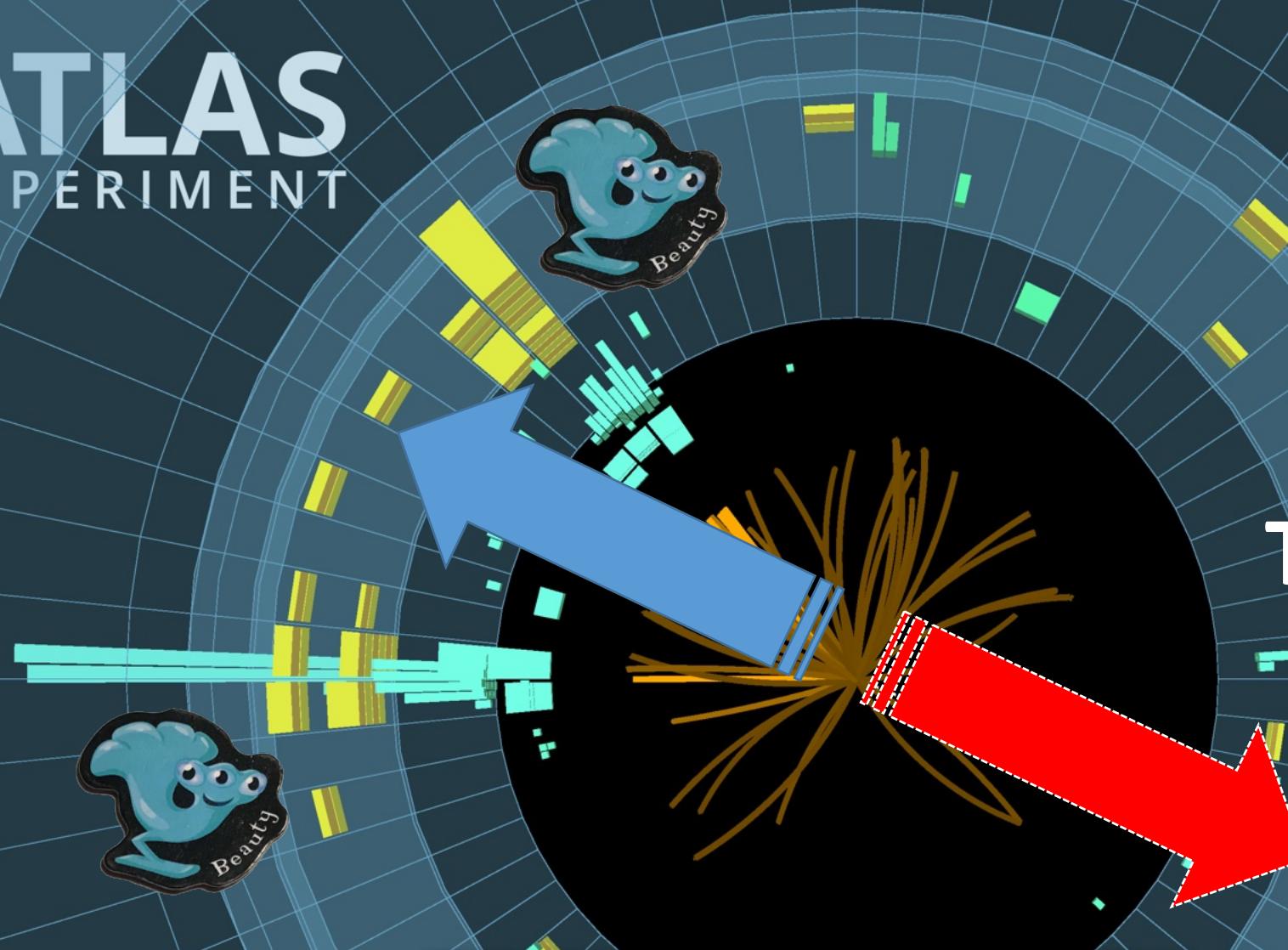


Fehlender
Transversal
impuls



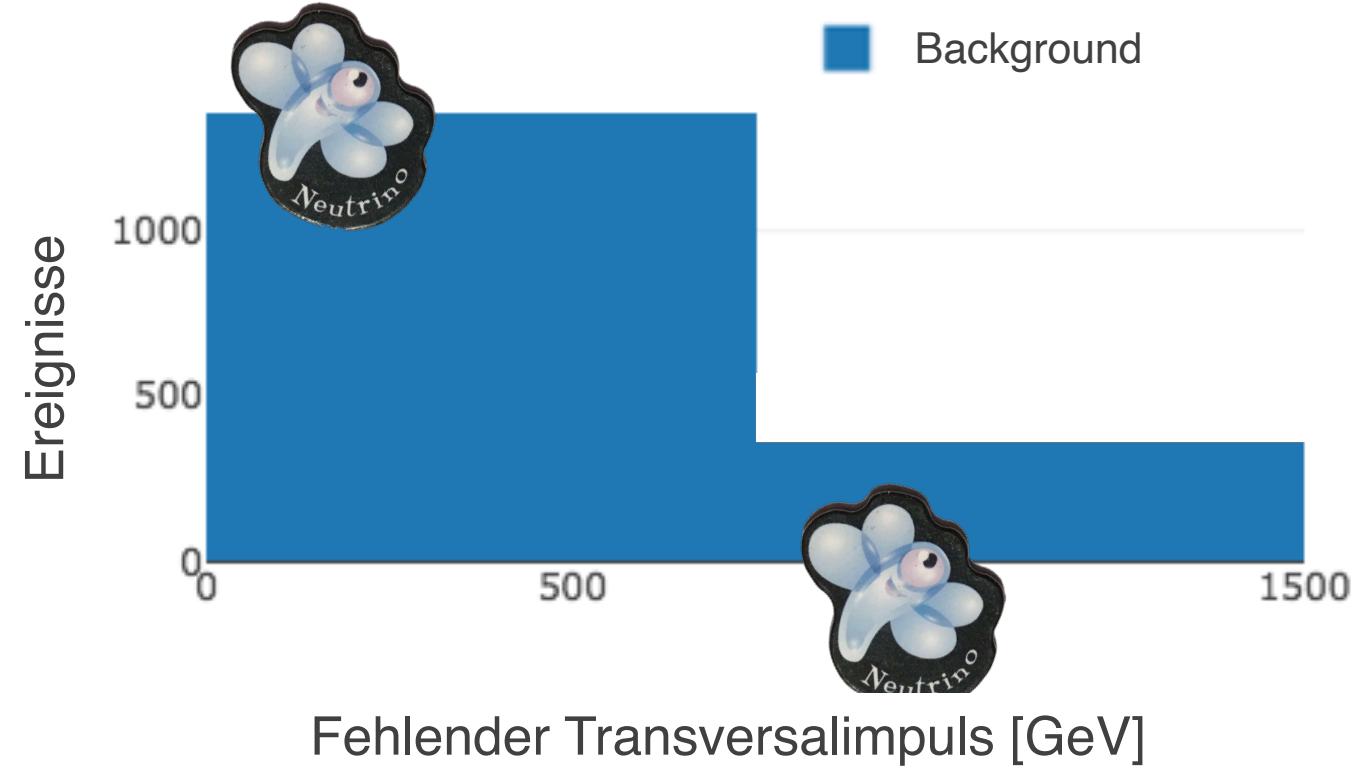


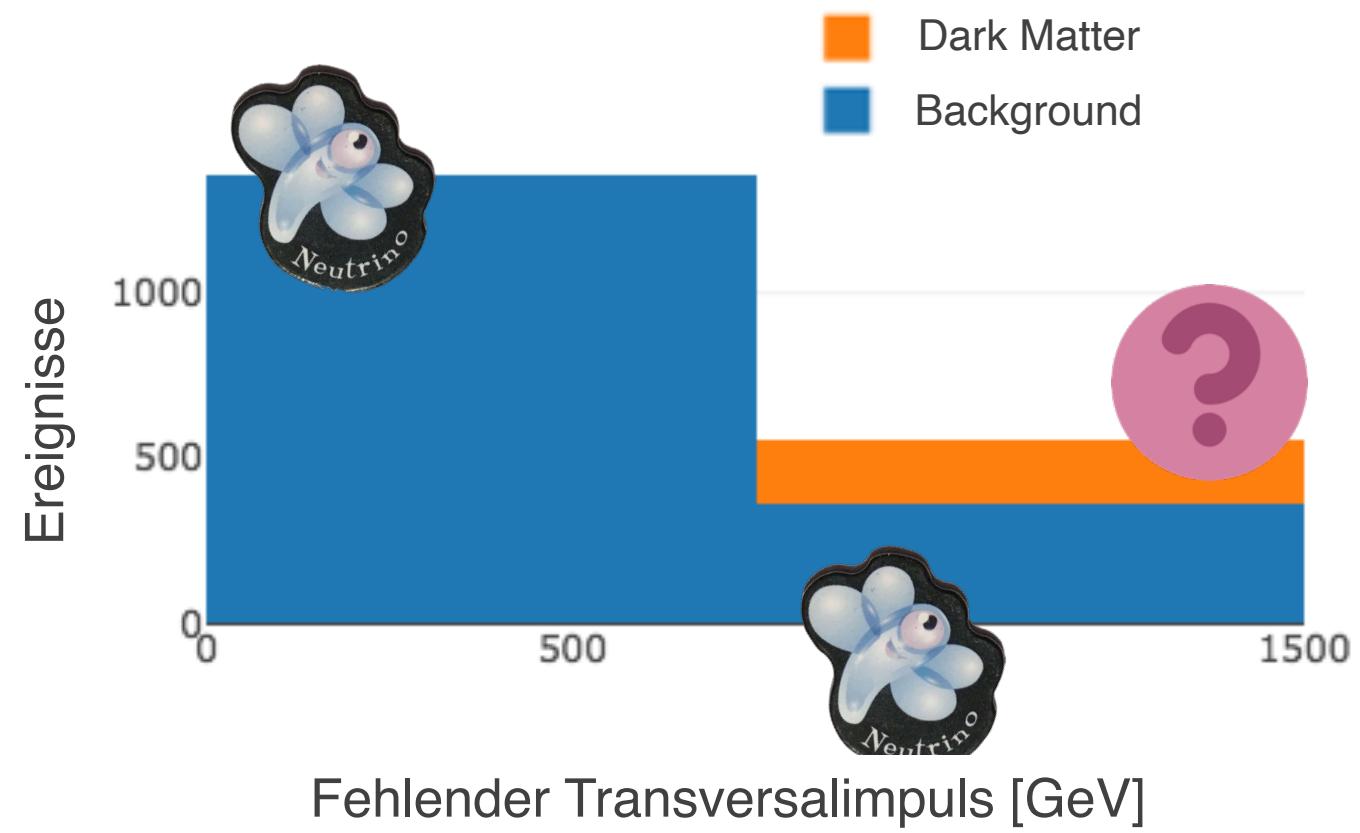
ATLAS
EXPERIMENT

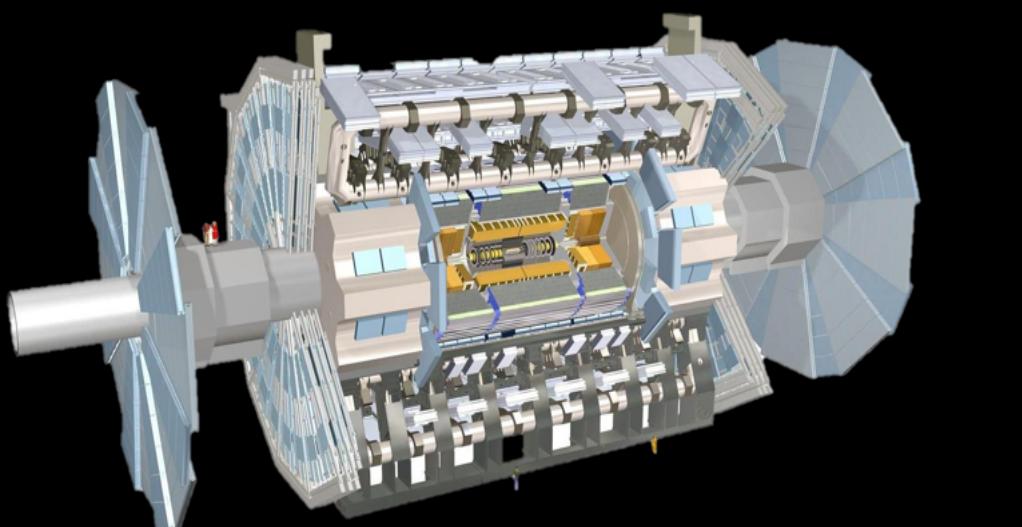


Fehlender
Transversal
impuls

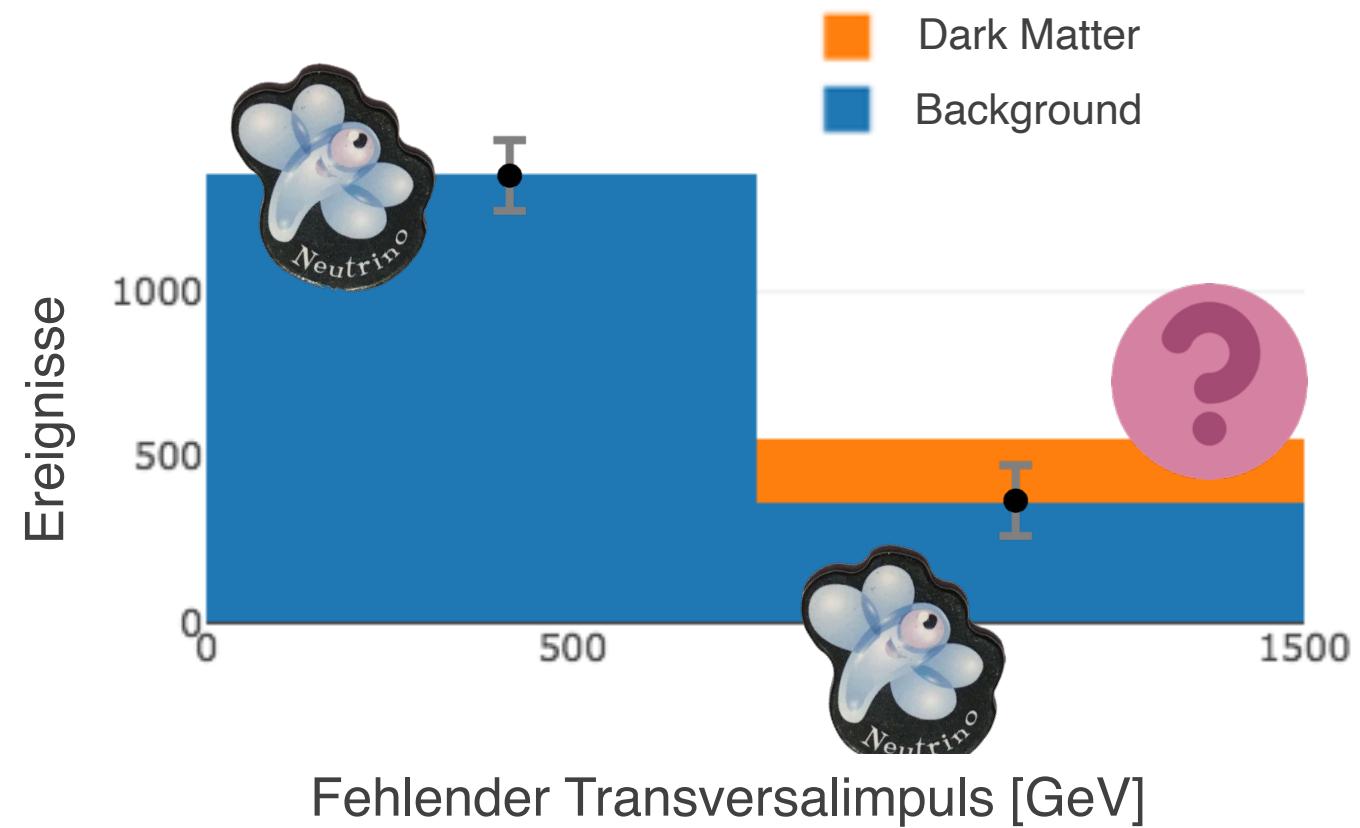
Untergrund

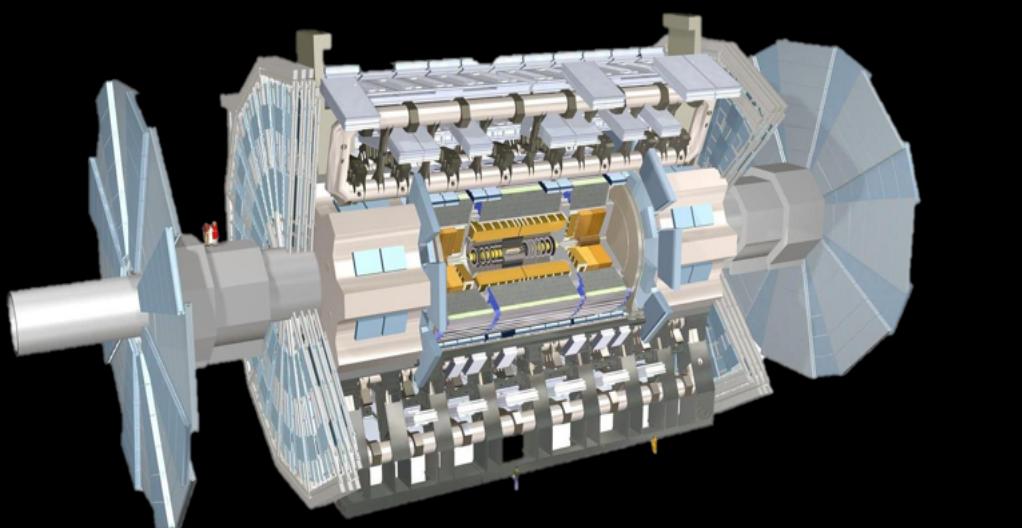




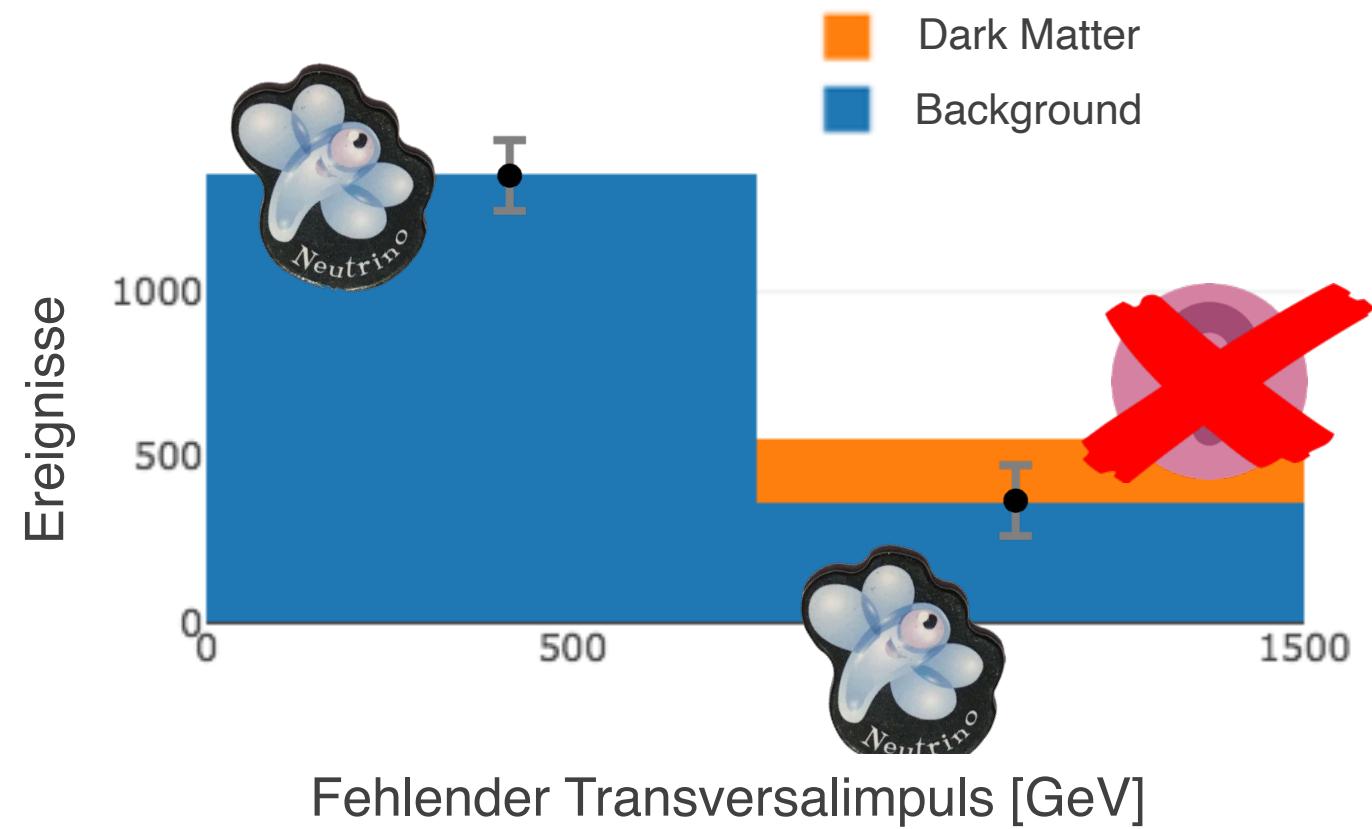


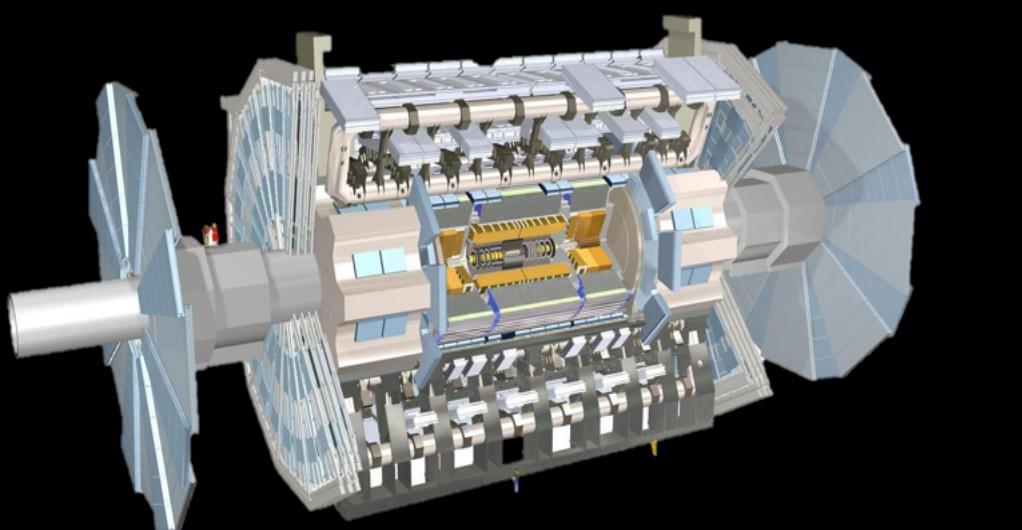
ATLAS Experiment © 2016 CERN



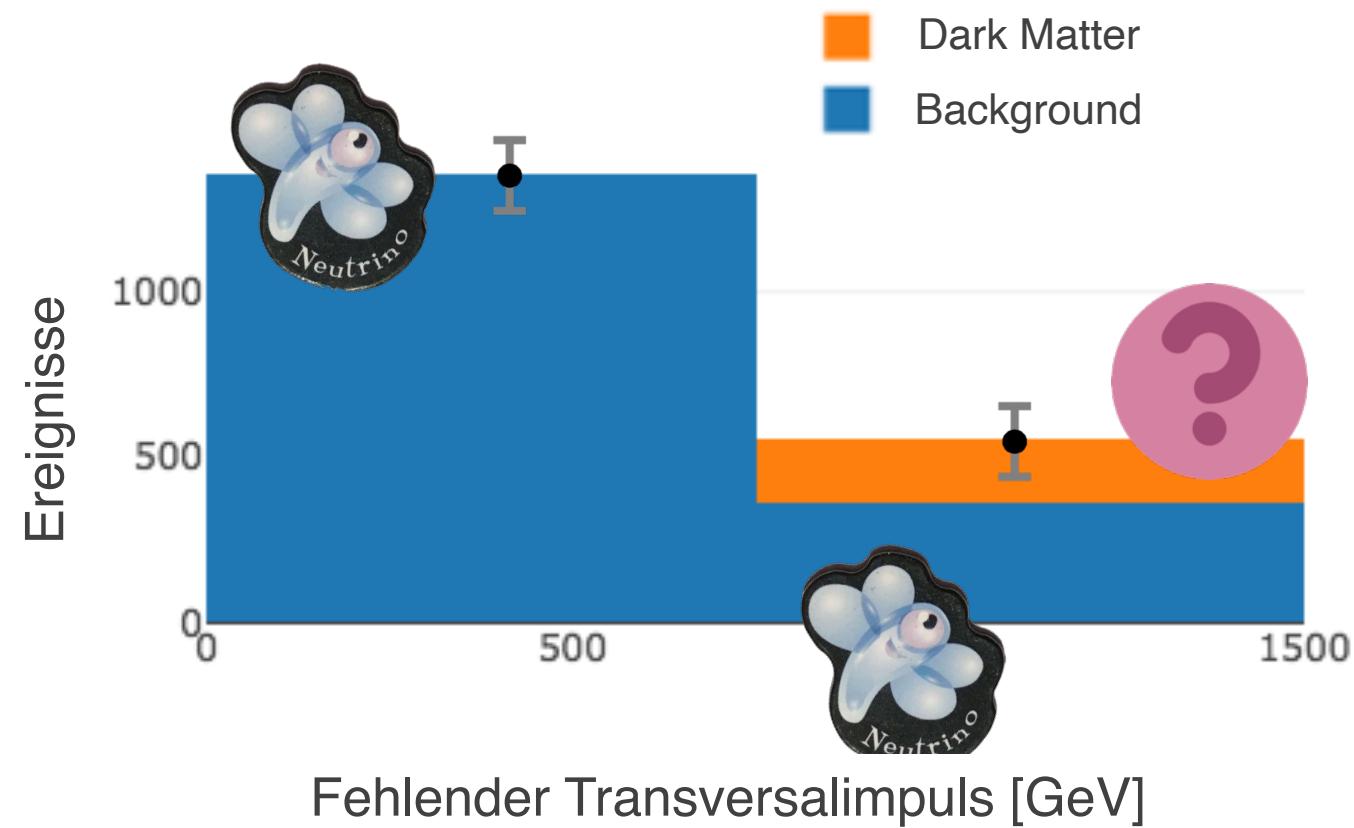


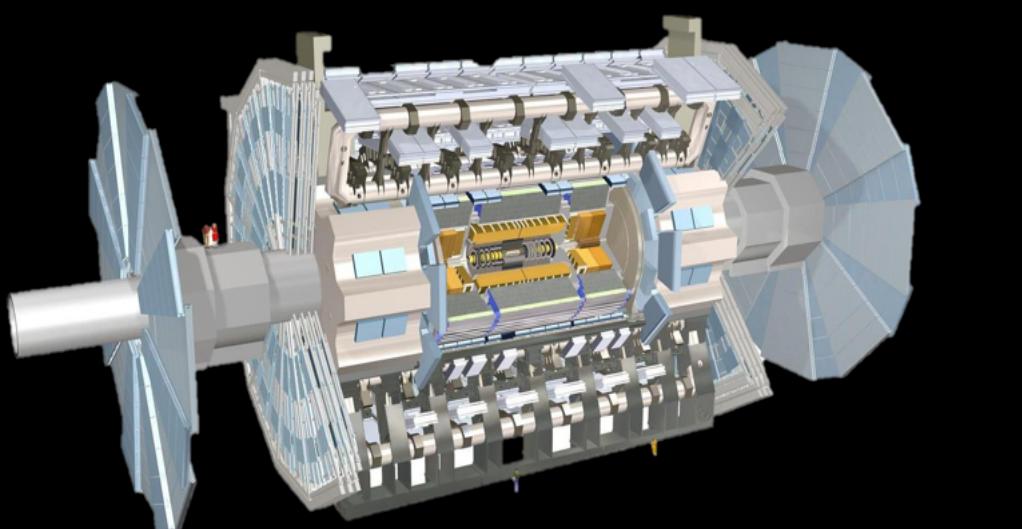
ATLAS Experiment © 2016 CERN



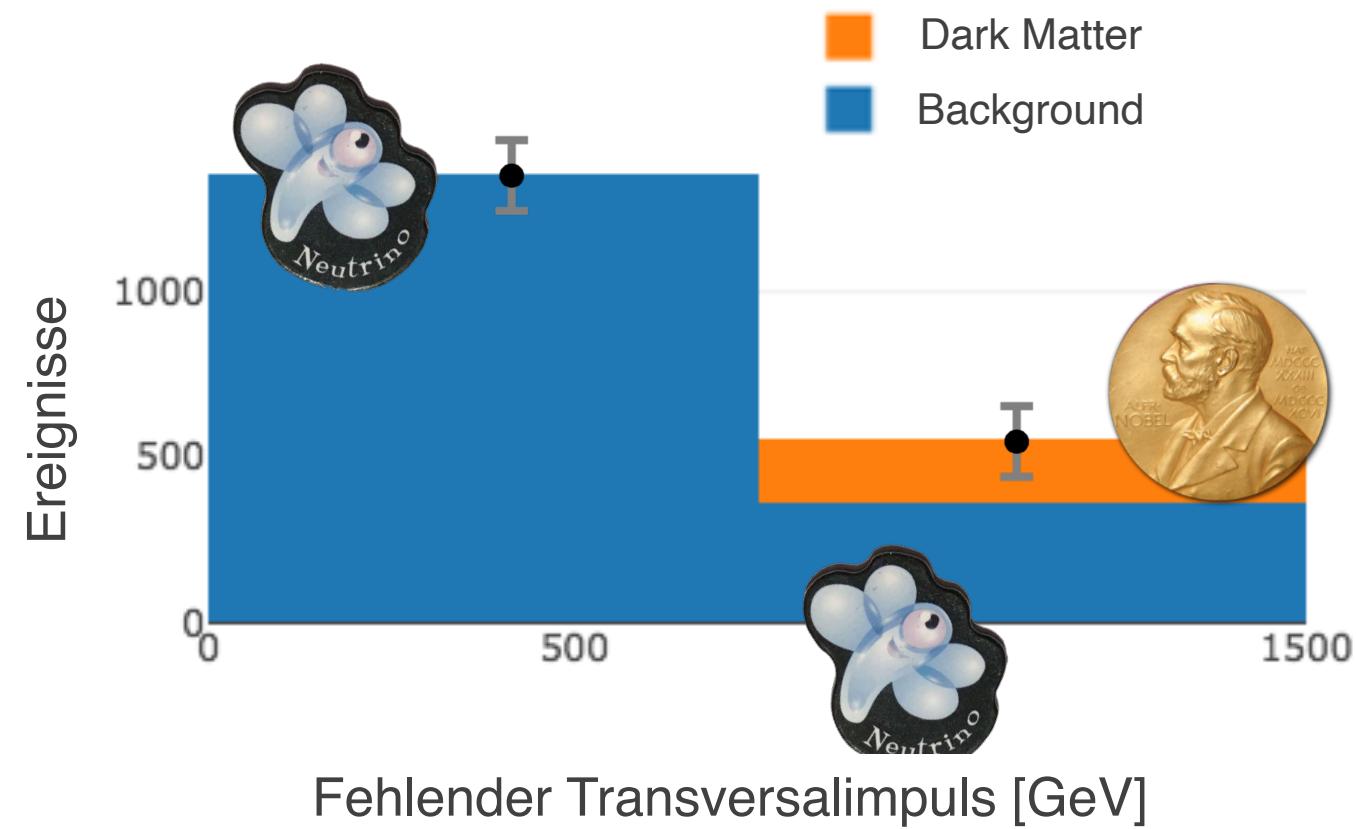


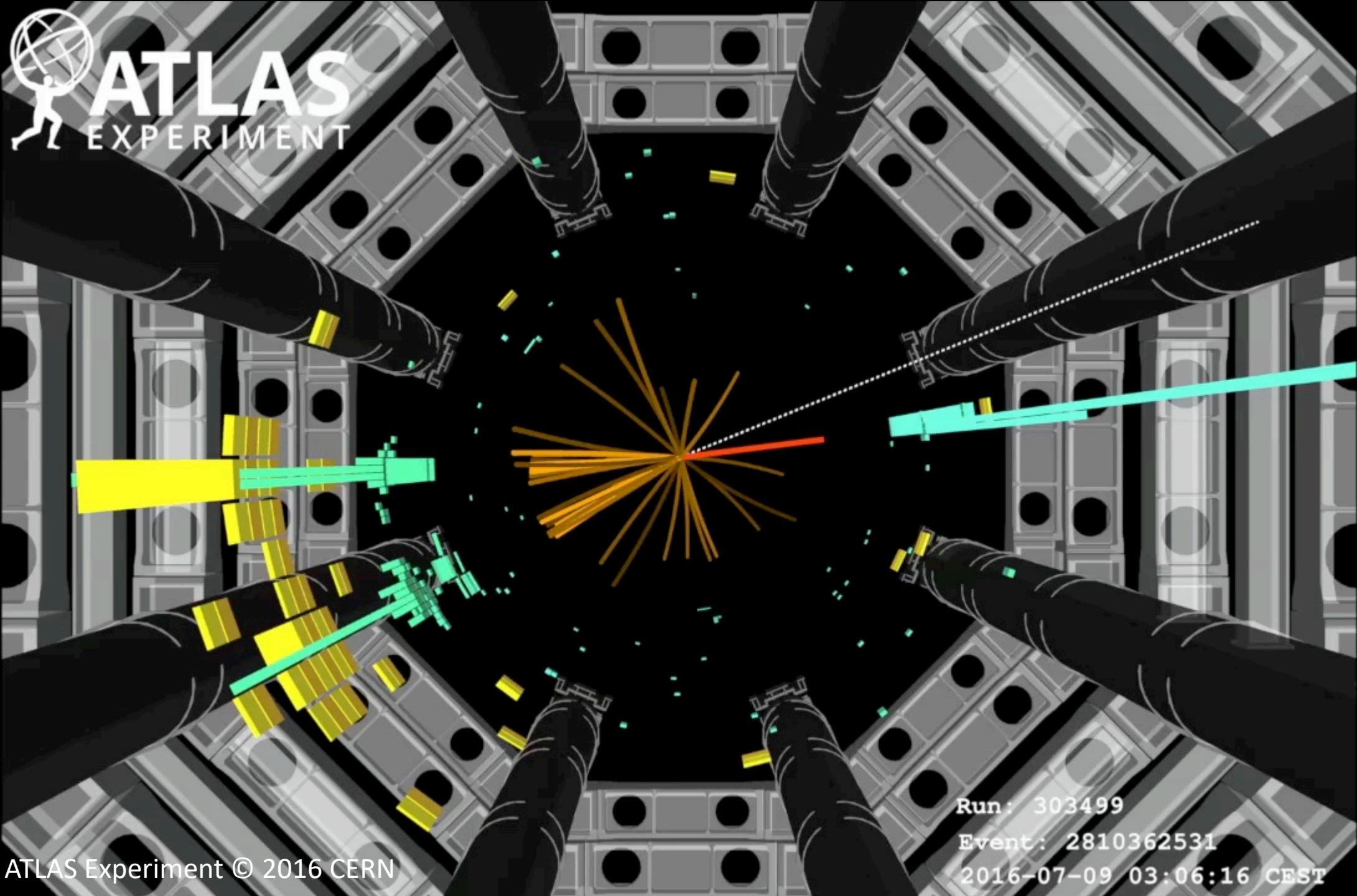
ATLAS Experiment © 2016 CERN





ATLAS Experiment © 2016 CERN





ATLAS Experiment © 2016 CERN

Run: 303499

Event: 2810362531

2016-07-09 03:06:16 CEST

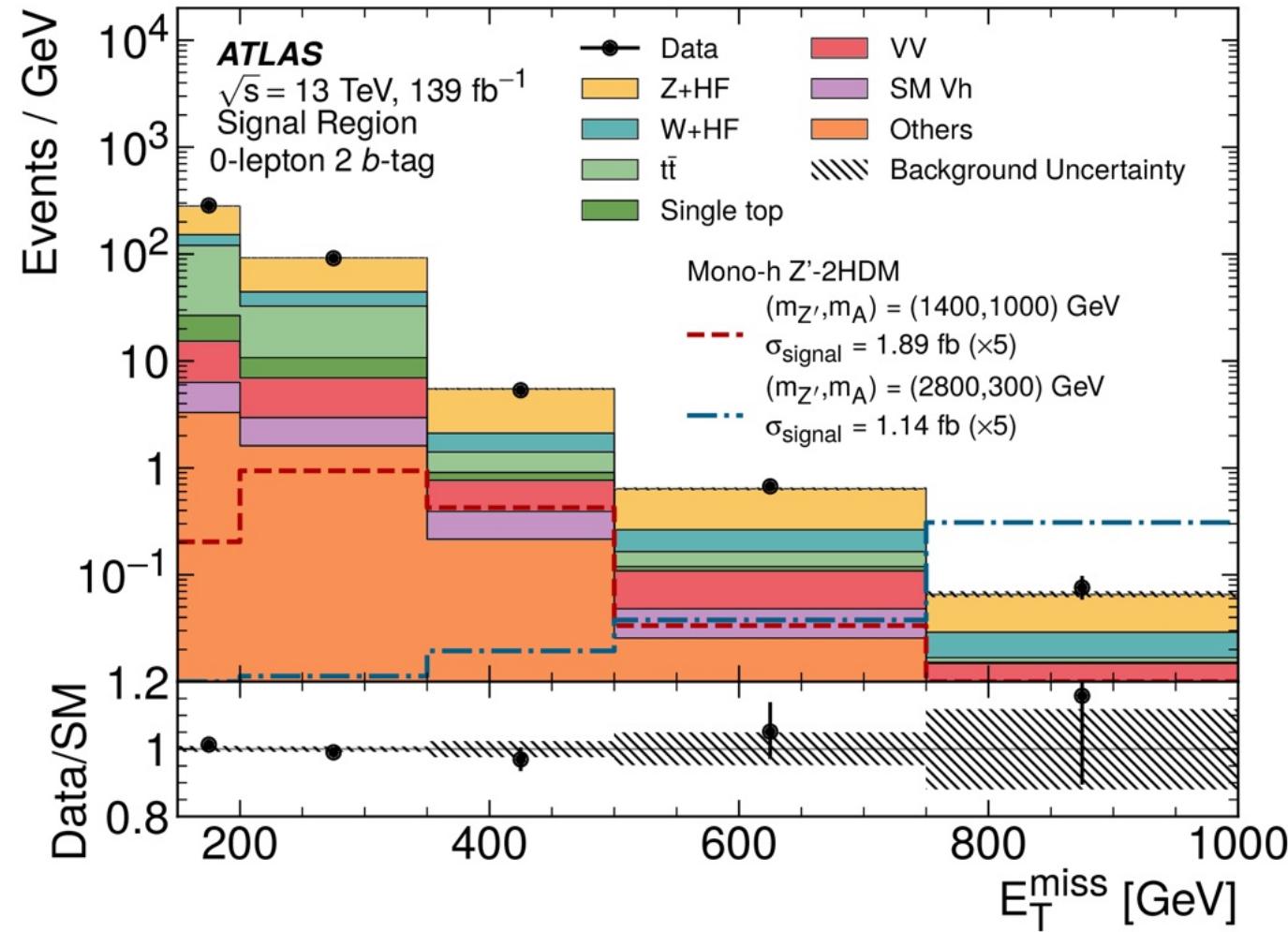


Submitted to: JHEP

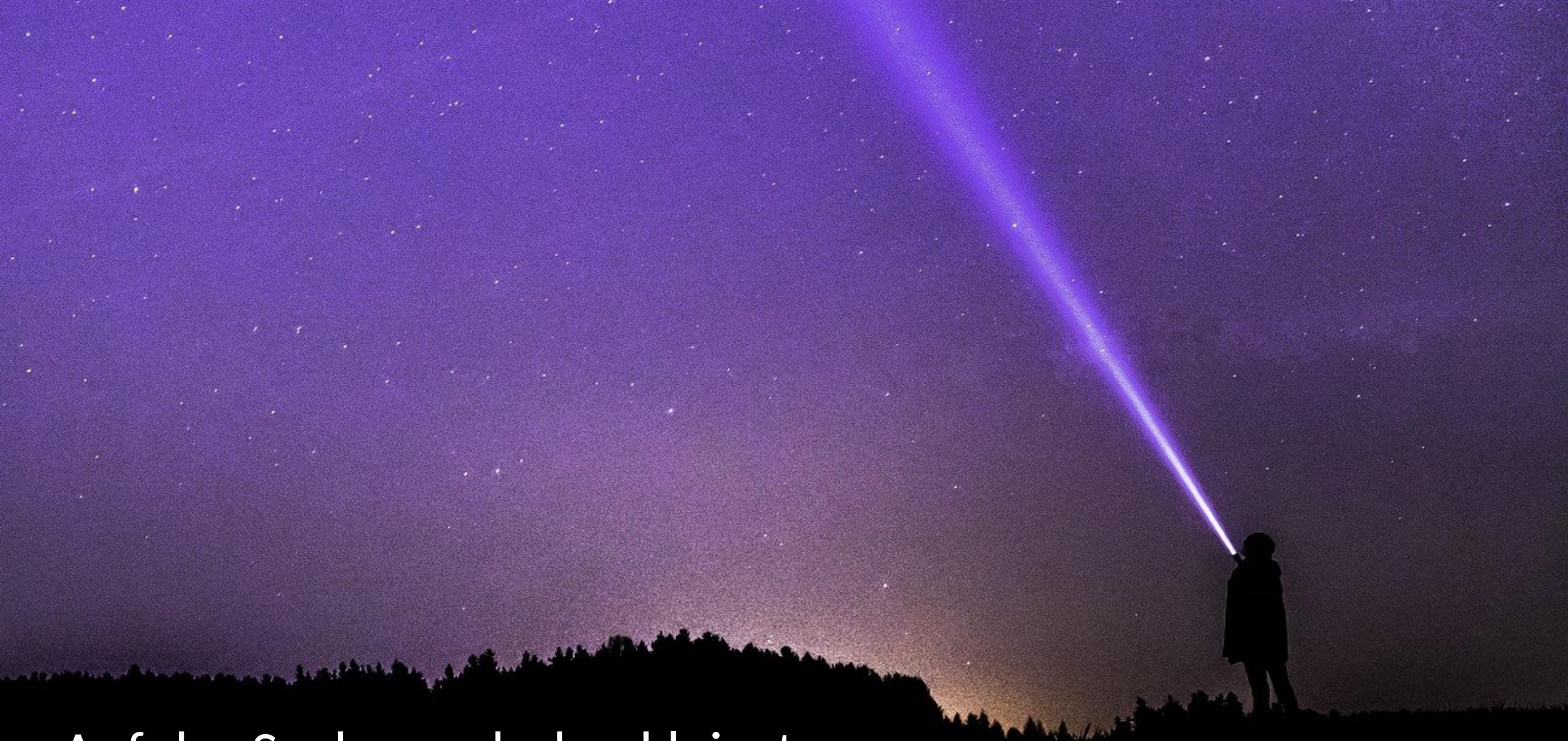
CERN-EP-2021-074
31st August 2021

**Search for dark matter produced in association
with a Standard Model Higgs boson decaying into
 b -quarks using the full Run 2 dataset from the
ATLAS detector**

The ATLAS Collaboration







Auf der Suche nach den kleinsten
Bausteinen der Welt am CERN



home.cern