

LHC run-2: Von den Ufern bekannter zu unbekannter Physik

Roger Wolf

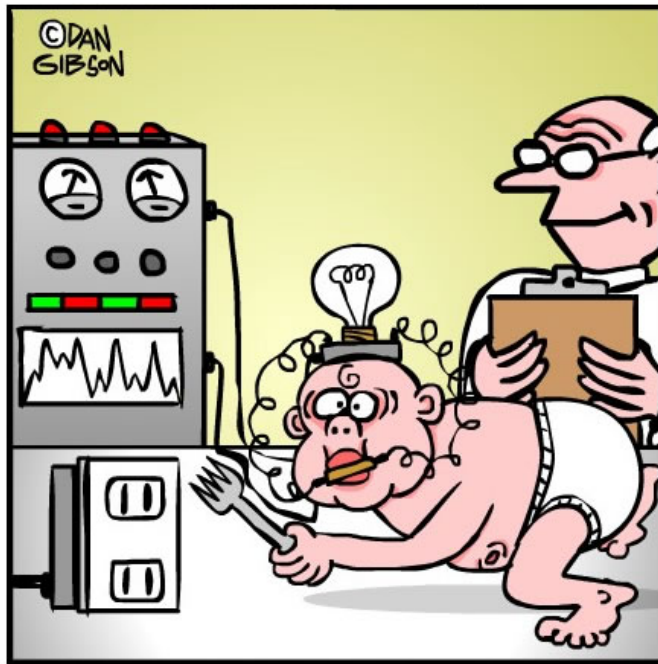
02. November 2016



Die Physik als moderne Naturwissenschaft

Experiment:

Reproduzierbare Naturbeobachtung
unter kontrollierten Laborbedingungen.



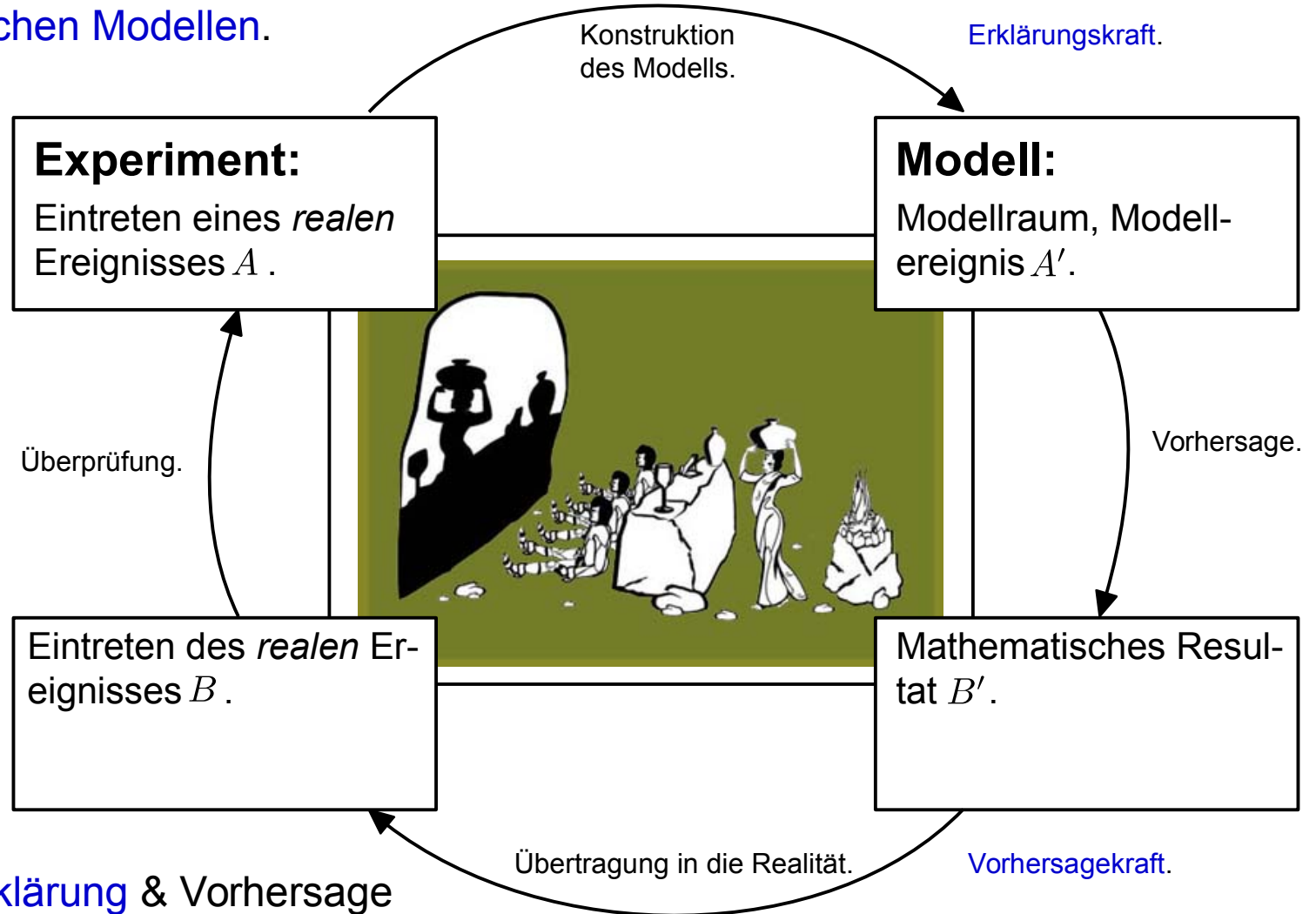
Dr. Finch conducting his controversial study on infants and their fascination with sticking forks in wall sockets.

Vorhersage:



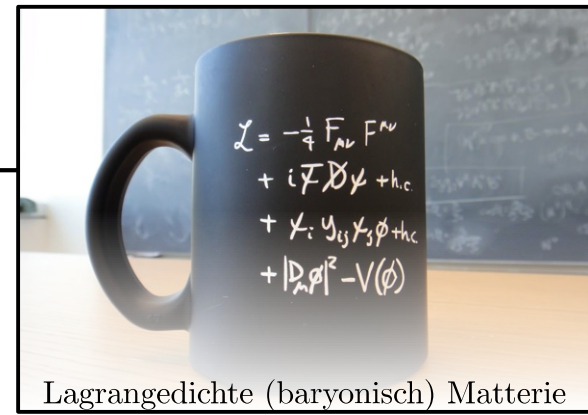
Vorhersagen in der Naturwissenschaft

- Seit der **Frühmoderne** geleitet von **mathematischen Modellen**.



- **Einfache Erklärung** & Vorhersage reproduzierbarer Naturereignisse.

Das Standardmodell der Teilchenphysik



	Fermions			Bosons	
Quarks	<i>u</i> up	<i>c</i> charm	<i>t</i> top	γ photon	Force carriers
	<i>d</i> down	<i>s</i> strange	<i>b</i> bottom	<i>Z</i> Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	<i>W</i> W boson	
	<i>e</i> electron	μ muon	τ tau	<i>g</i> gluon	
spin-1/2				Higgs boson	

Source: AAAS

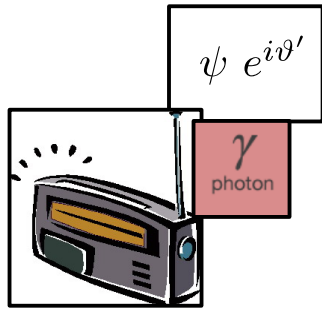
Beschreibung der ursprünglichen Struktur der uns umgebenden Natur.

$$U(1)_Y \times SU(2)_L \times SU(3)_c$$

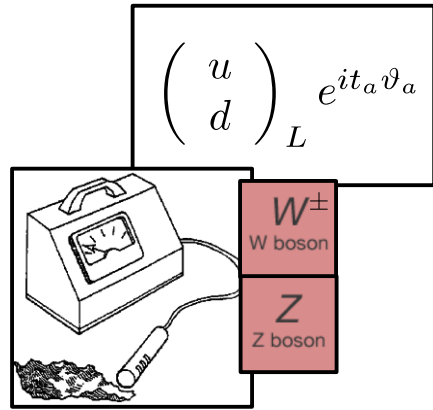
1d Drehungen

2d Drehungen

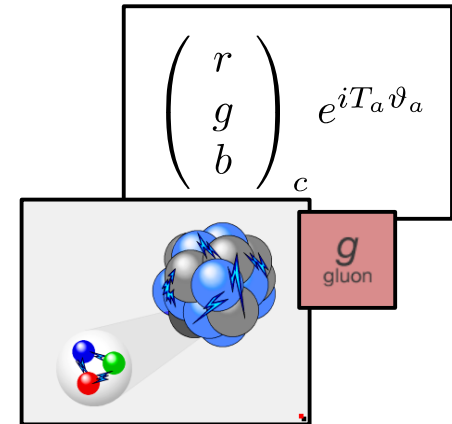
3d Drehungen



Elektromagnetismus



Schwache Kraft

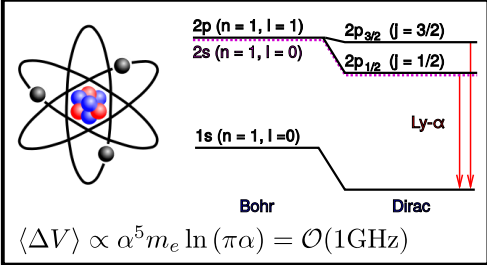


Starke Kraft

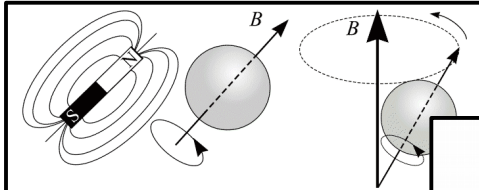
- Bezieht Erklärungs-/Vorhersagekraft aus Anwendung von Symmetrien!
- Kräfte ↔ masselose Vermittlerteilchen.

Phänomene der Teilchenphysik

Lamb shift: (Präzision $\mathcal{O}(10^{-7})$)



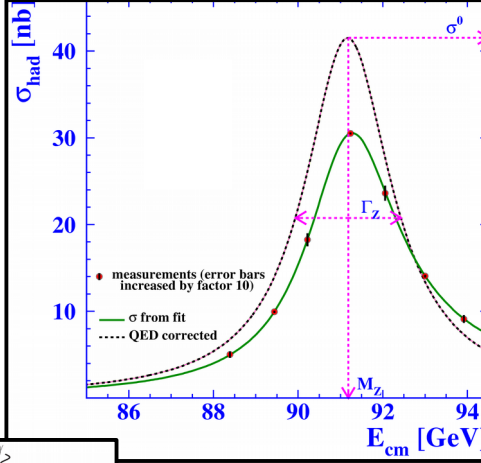
Anormales Magnetisches Moment des Myons: (Präzision $\mathcal{O}(10^{-9})$)



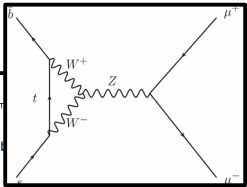
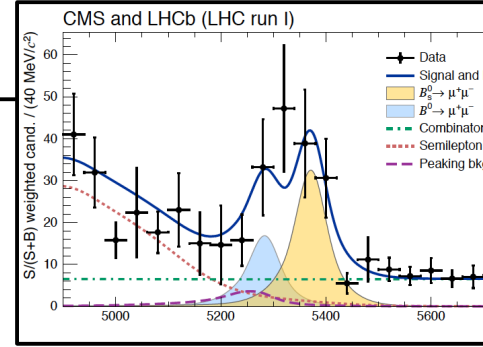
$$\frac{(g-2)}{2} = 0.00115965218073(28)$$

Präzisionsmessungen:

LEP: (Präzision $\mathcal{O}(10^{-5})$)

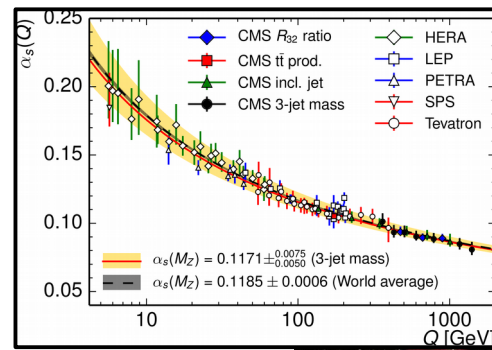


Rare decays: (Präzision $\mathcal{O}(10^{-9})$)

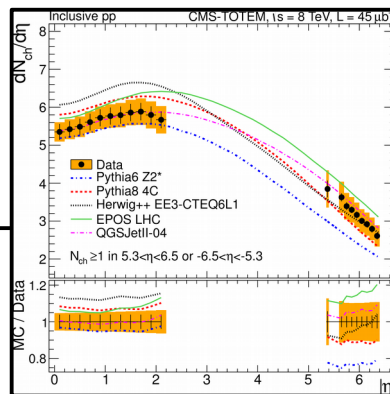


“Striking features” & globale Eigenschaften:

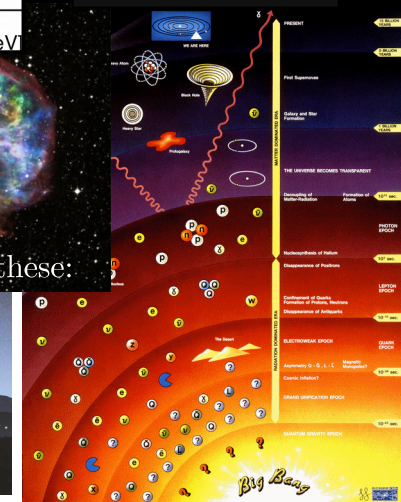
Asymptotische Freiheit:



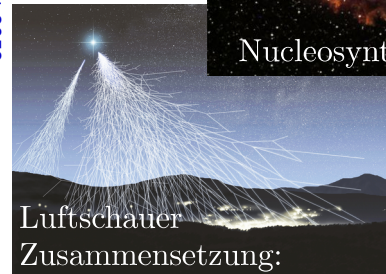
Inclusive pp Streuung:



Geschichte des Universums:

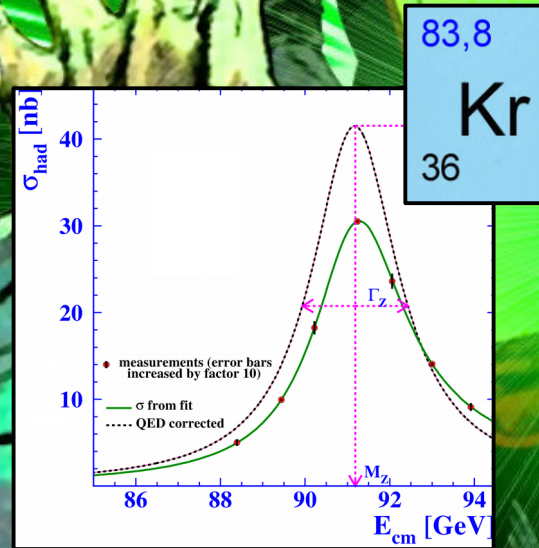


Nucleosynthese:

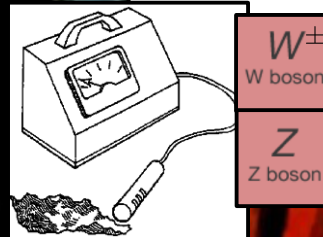


- Bezieht Erklärungs-/Vorhersagekraft aus Anwendung von Symmetrien!
- Kräfte ↔ masselose Vermittlerteilchen.

Vermittlerteilchen mit Masse brechen vorrausgesetzte Symmetrien explizit!



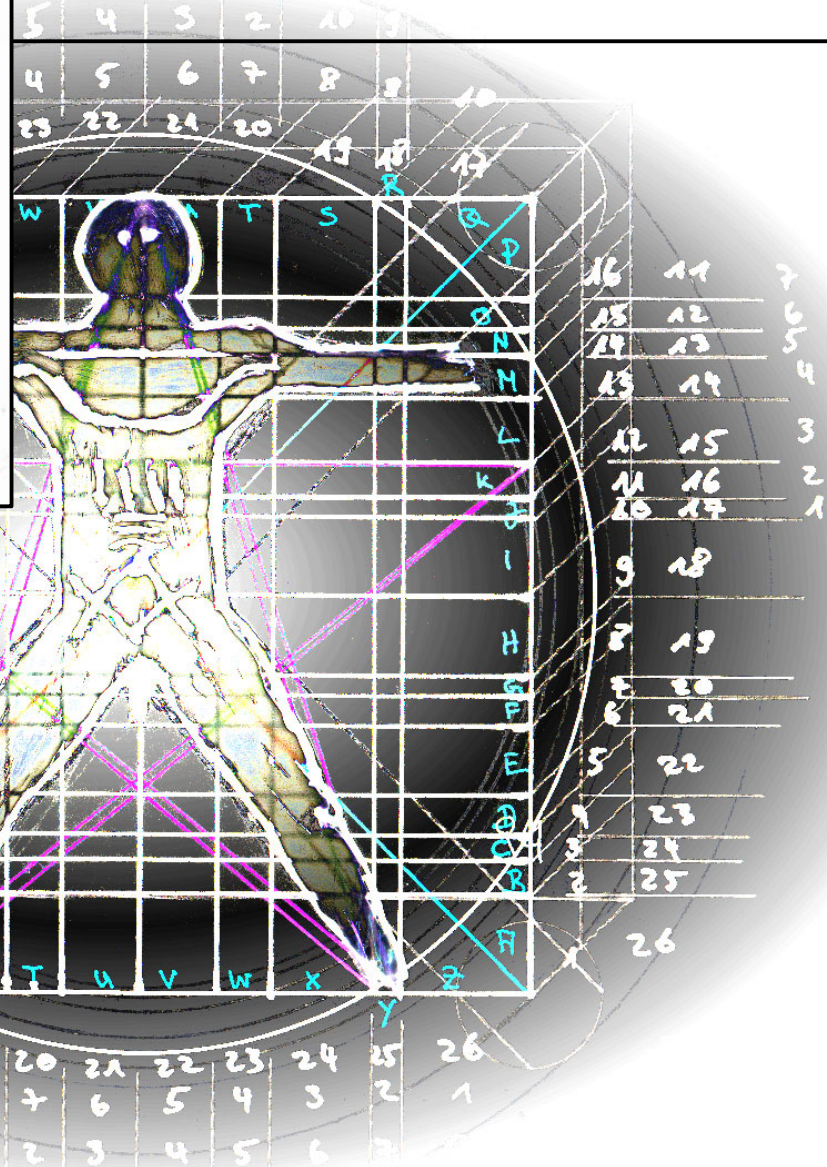
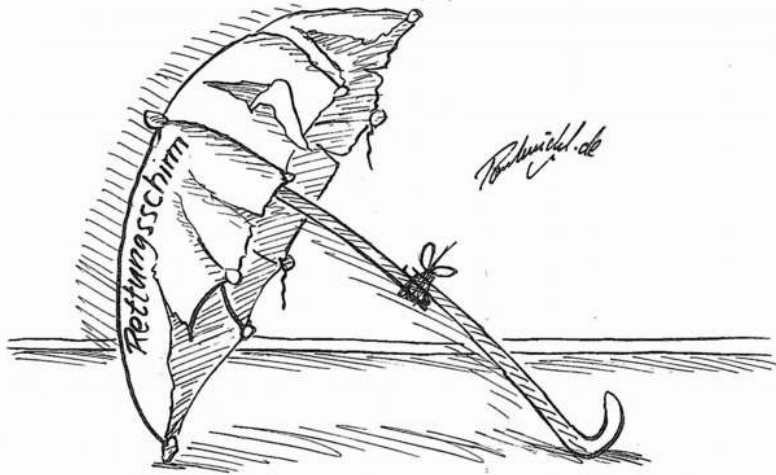
$$\begin{pmatrix} u \\ d \end{pmatrix}_L e^{it_a \vartheta_a}$$



• Bezieht Erklärungs-/Vorhersagekraft aus Anwendung von Symmetrien!

• ~~Kräfte \leftrightarrow masselose Vermittlerteilchen.~~

Wie kann eine Symmetrie zur gleichen Zeit erhalten und gebrochen sein?



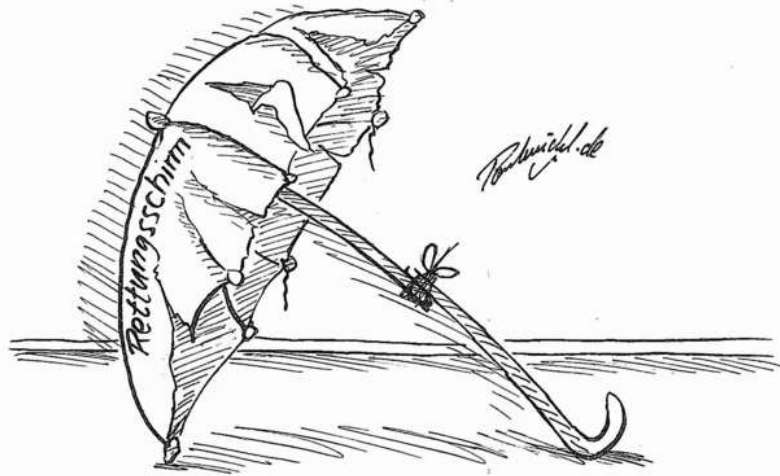
hebr.
stadi

	19	8
	18	9
1	17	10
2	16	11
3	15	12
4	14	13
5	13	14
6	12	15
7	11	16

16	11	7
15	12	6
14	13	5
13	14	4
12	15	3
11	16	2
10	17	1
9	18	
8	19	
7	20	
6	21	
5	22	
4	23	
3	24	
2	25	
1	26	

Flächen
= (r x 2π)

Wie kann eine Symmetrie zur gleichen Zeit erhalten und gebrochen sein?



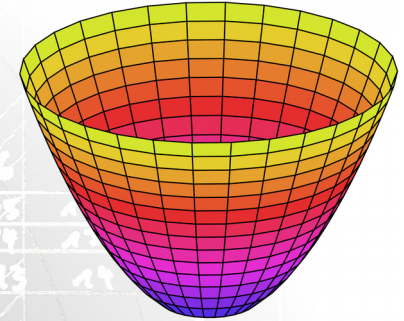
Spontane Symmetriebrechung:

$$f(x, y) = x^2 + y^2$$

$$x = r \cos \varphi$$

$$y = r \sin \varphi$$

$$f(x, y)|_{r, \varphi} = r^2 (\cos^2 \varphi + \sin^2 \varphi) = r^2$$



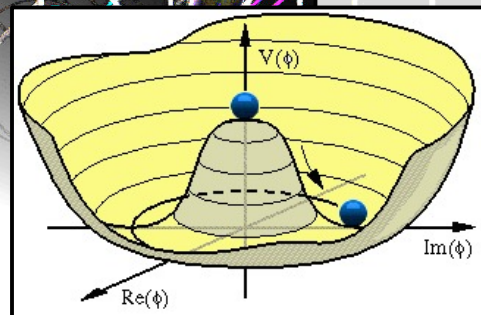
$$\tilde{f}(x, y) = (x - 1)^2 + (y - 1)^2$$

$$\tilde{f}(x, y)|_{r, \varphi} = r^2 + 2(1 - r(\sin \varphi + \cos \varphi))$$

("hidden symmetry")

Führe Potential ein das den Grundzustand des Universums aus der Symmetrieachse der Bewegungsgleichungen zwingt.

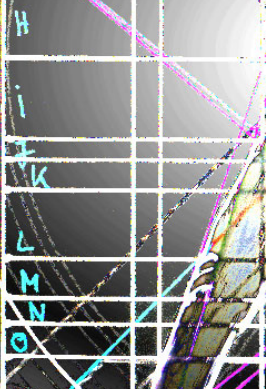
→ Teilchenmasse als Kopplung an nicht verschwindenden Vakuumerwartungswert.




hebe

stade

1	19	8
2	18	9
3	17	10
4	16	11
5	15	12
6	14	13
7	13	14
	12	15
	11	16



Drei Säulen des Standardmodells



Quantenfeldtheorie

- Relativistische QM.
- Erzeugung/Vernichtung von Teilchen.

Symmetriebrechung

- Teilchenmasse.

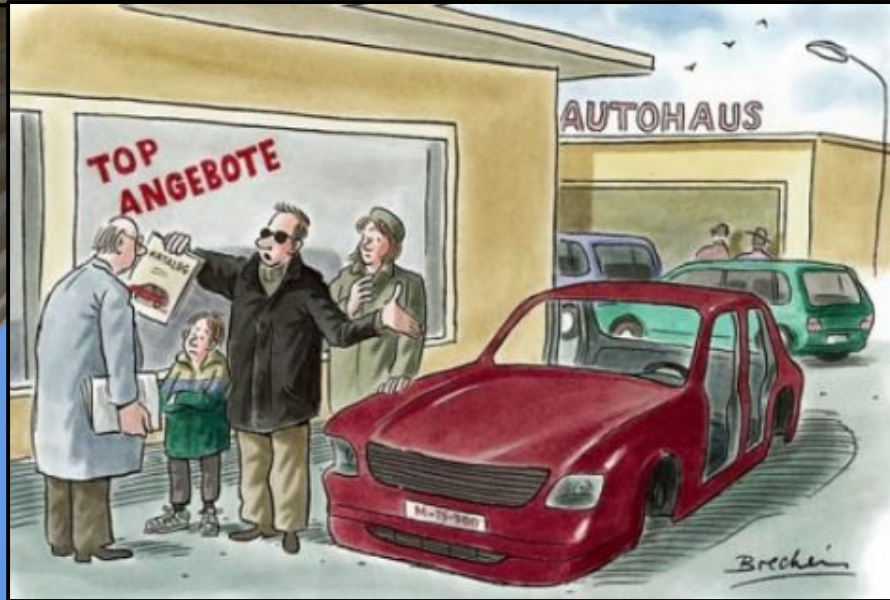
Symmetrien

- Fundamentale WW.
- Struktur der Materie

Drei Säulen des Standardmodells

Quantenfeldtheorie

- Relativistische QM.
- Erzeugung/Vernichtung von Teilchen.



Symmetriebrechung

- Teilchenmasse.

Symmetrien

- Fundamentale WW.
- Struktur der Materie

Drei Säulen des Standardmodells

Postulat eines neuen Teilchens (→ Higgs Boson) mit einzigartigem Kopplungsverhalten ($\propto m$).

- Relativistische QM.
- Erzeugung/Vernichtung von Teilchen.

1961: Vereinheitlichte Theorie der elektroschwachen Wechselwirkung.

1962: Spontane Symmetriebrechung in Spraleitung.

1964: **Higgs Mechanismus** in der Teilchenphysik.

1967: Formulierung Standardmodell in heutiger Form.

1974-77: Entdeckung schwerer Quarks und Leptonen.

1983: Entdeckung W und Z Bosonen.

1995: Entdeckung *top* Quark.

2012: Entdeckung Higgs Boson.

2013: Nobelpreis Peter Higgs & Francois Englert.

Drei Säulen des Standardmodells

Postulat eines neuen Teilchens (→ Higgs Boson) mit einzigartigem Kopplungsverhalten ($\propto m$).

Nuclear Physics B106 (1976) 292–340
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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * & A. V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^+ p \rightarrow H n$ or $\gamma p \rightarrow H p$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new neutrinos.

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

taken from R. Harlander, 2014

- 1961: Vereinheitlichte Theorie der elektroschwachen Wechselwirkung.
- 1962: Spontane Symmetriebrechung in Spralleitung.
- 1964: **Higgs Mechanismus** in der Teilchenphysik.
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Higgs Suche

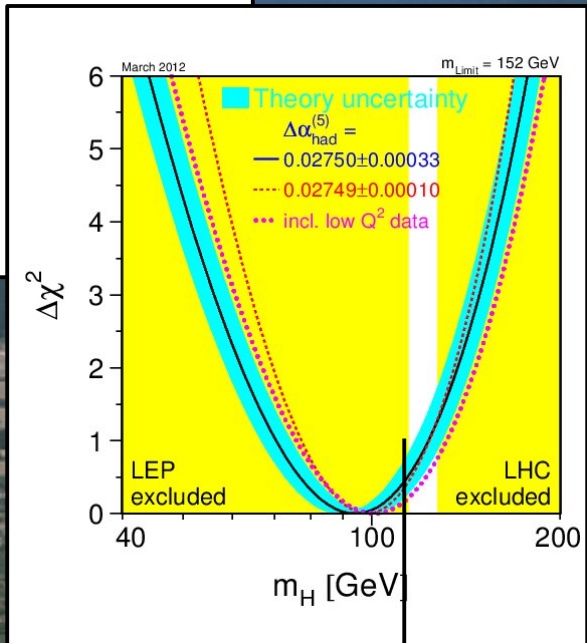
LEP (1989 – 2000):

Modellanpassung an 18 Präzisions-
observablen:

$$\mathcal{P}(\chi^2) = 20.2\%^{(1)}$$

$$m_H = 98 \pm_{21}^{25} \text{ GeV}$$

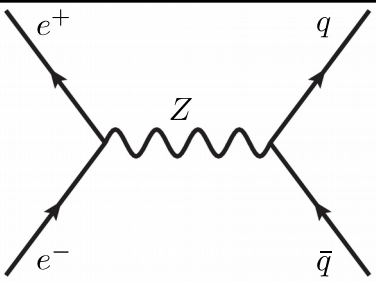
$$m_H \leq 152 \text{ GeV (95\% CL)}$$



Direkte Suchen: \blacktriangledown

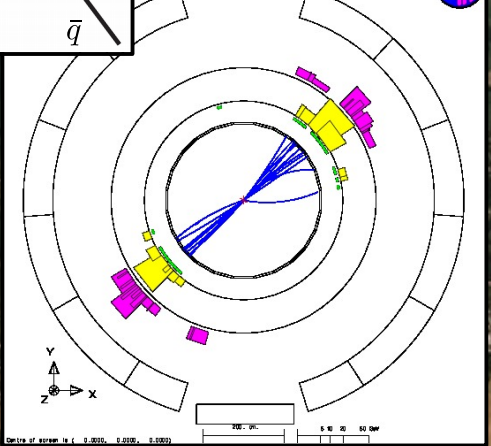
$$m_H \geq 115 \text{ GeV (95\% CL)}$$

⁽¹⁾ $\chi^2/\text{ndof} = 16.9/13$



$15 \cdot 10^6 \text{ } Z \rightarrow q\bar{q}$

File: 20140314 (No. 33 Supp. 13.3) Est. (No. 25 Sur6. 32.6) Hcal (No.22 Sur6. 22.6) B Vtx (-0.07, 0.06, -0.90) Moon (No. 0) Src. (No. 5) Fcst (No. 0 Sur6. 0.0) 10/20/2014 10:58:00 AM



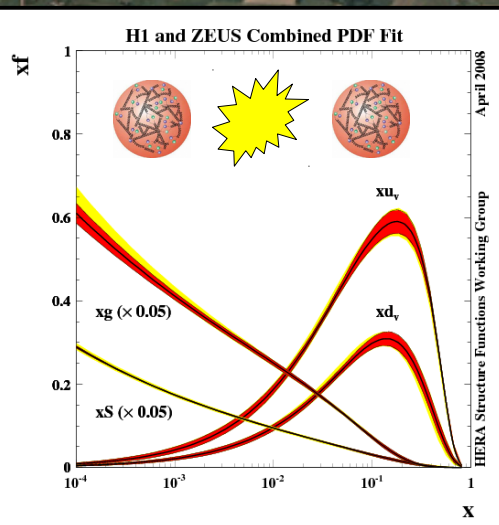
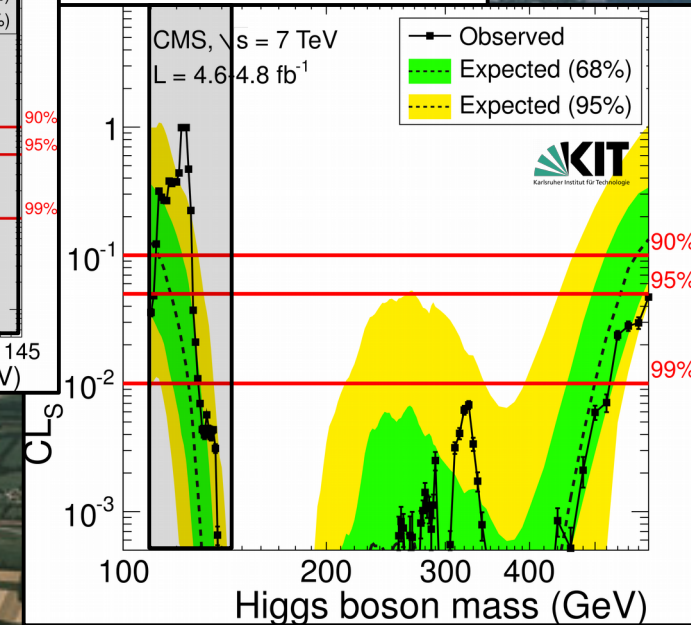
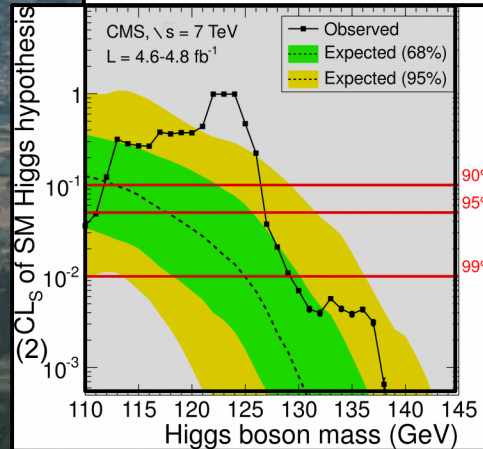
Higgs Suche

LHC (2011):

Direkte Suchen nach dem SM Higgs
Boson (1/5 LHC run-1):

$$m_H \leq 124 \text{ GeV} \quad (3.1 \sigma \text{ obs})$$

$$m_H \leq 127 \text{ GeV} \quad (95\% \text{ CL})$$



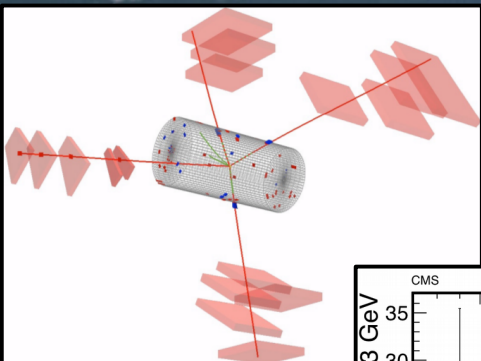
(2) Maß für Kompatibilität
mit Beobachtung.

Higgs Entdeckung

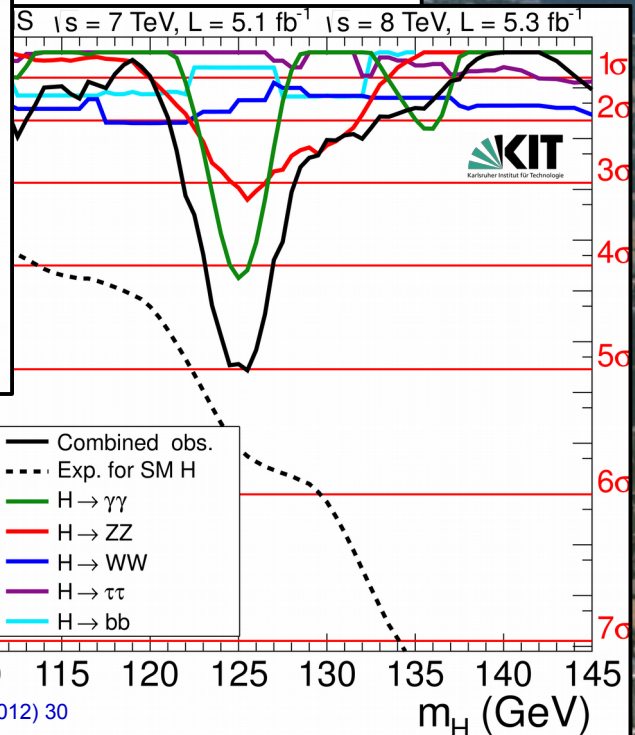
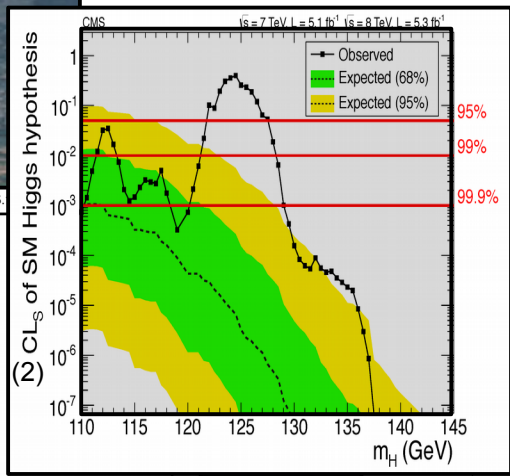
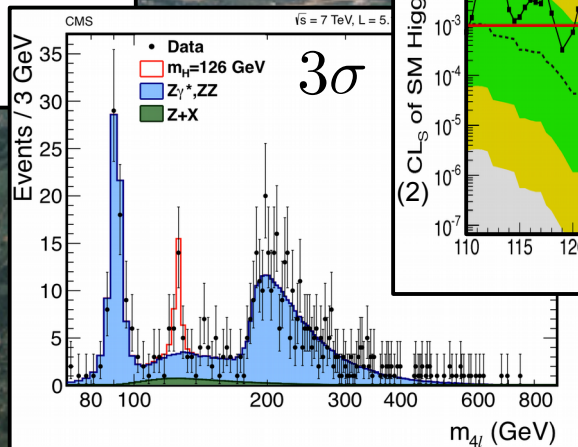
Direkte Suchen nach dem SM Higgs Boson (1/2 LHC run-1):

$$m_H \leq 125 \text{ GeV} \text{ (5.0 } \sigma \text{ beobachtet)}$$

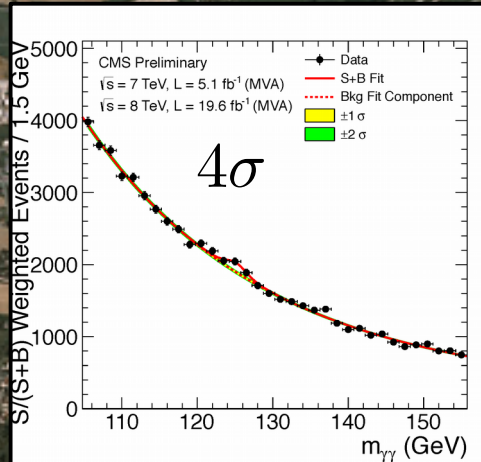
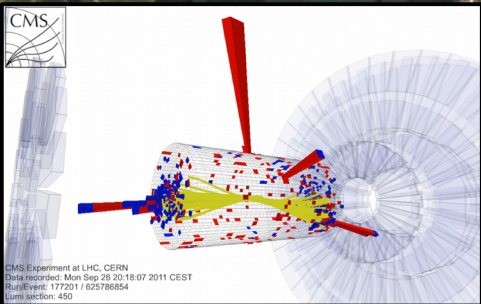
4. Julie 2012



$$H \rightarrow ZZ \rightarrow 4\ell$$



$$H \rightarrow \gamma\gamma$$



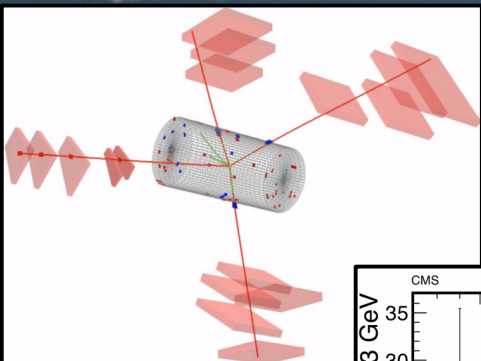
(2) Maß für Kompatibilität mit Beobachtung.

Higgs Entdeckung

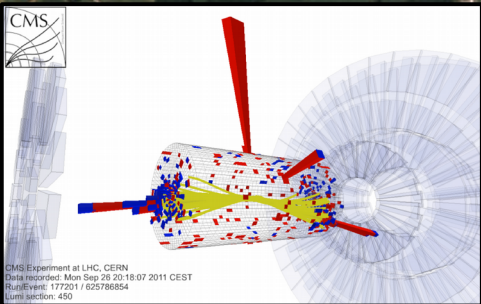
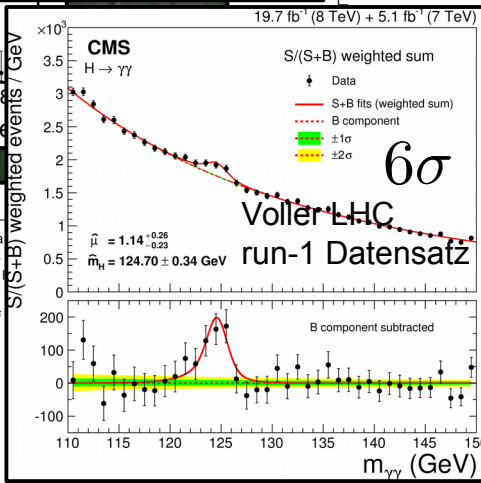
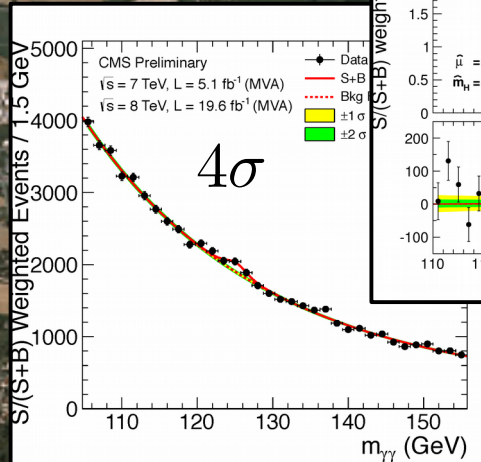
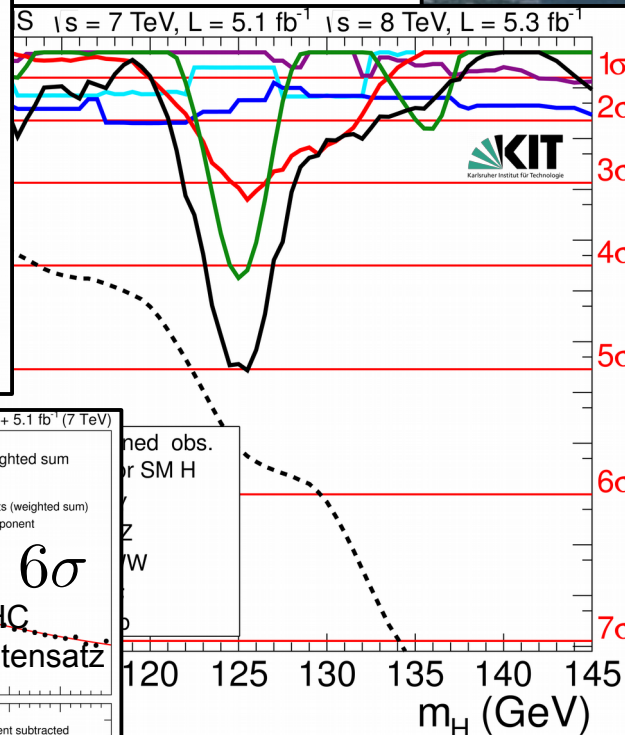
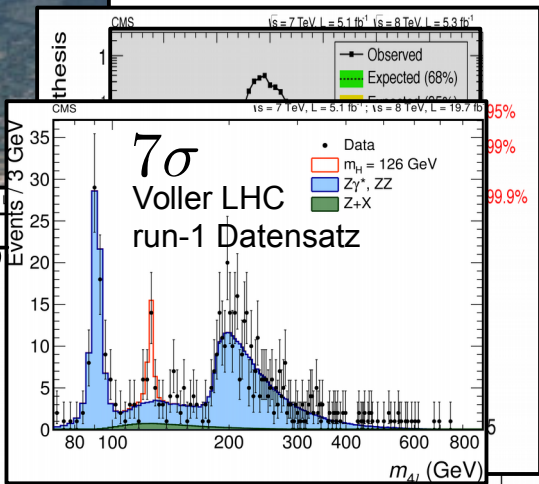
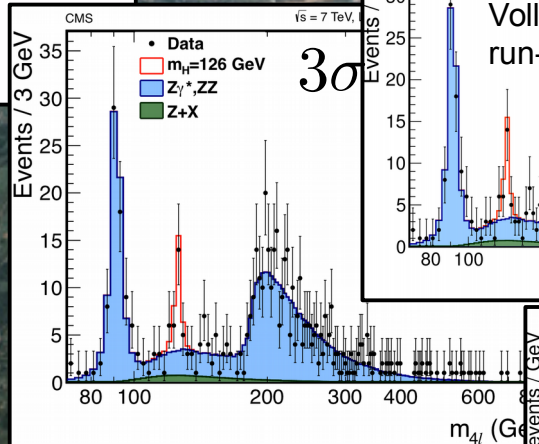
Direkte Suchen nach dem SM Higgs Boson (1/2 LHC run-1):

$$m_H \leq 125 \text{ GeV} \quad (5.0 \sigma \text{ beobachtet})$$

4. Julie 2012



$$H \rightarrow ZZ \rightarrow 4\ell$$



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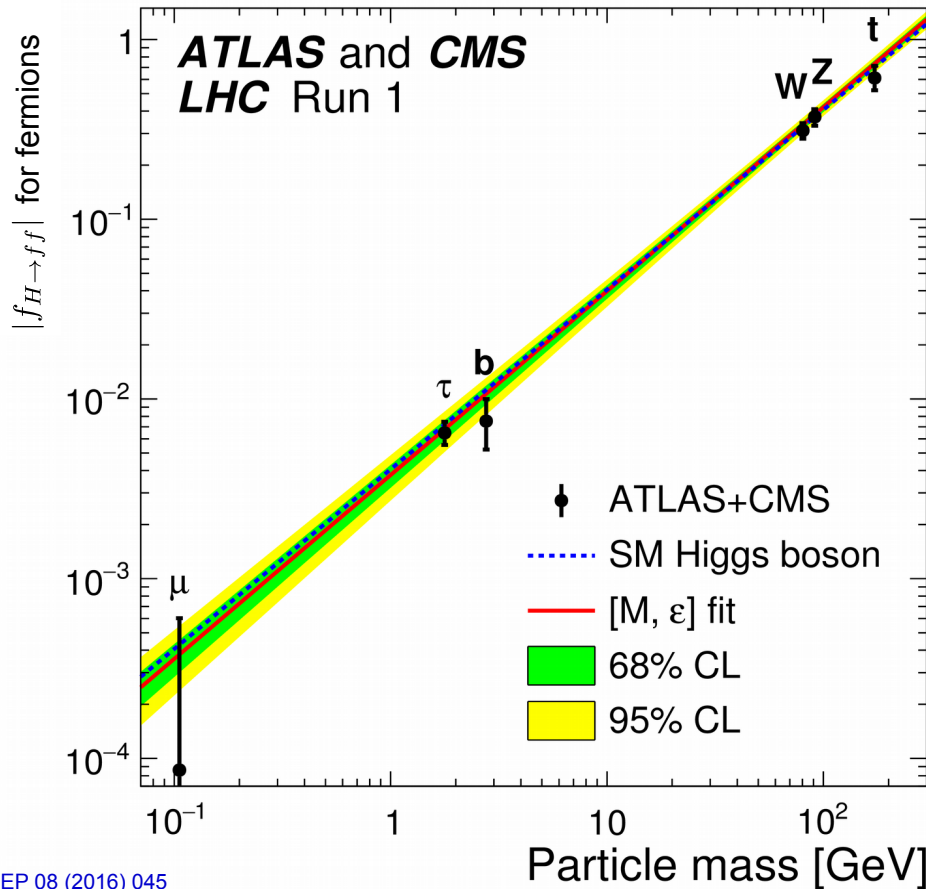
CMS Experiment at LHC, CERN
Data recorded: Mon Sep 28 20:18:07 2011 CEST
Runfile: 17201_162786054
Lumi section: 450

(2) Maß für Kompatibilität mit Beobachtung.

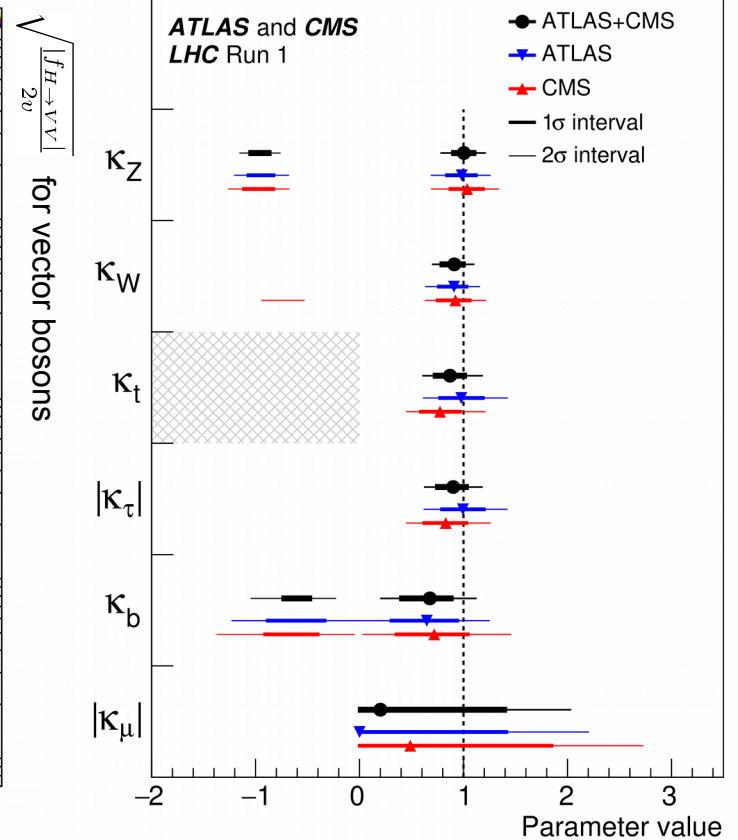
Higgs Boson Kopplungen



SM p -value = 40%



JHEP 08 (2016) 045



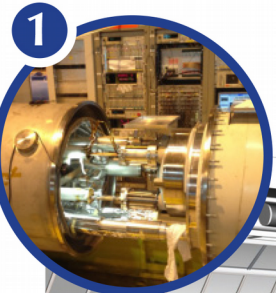
$$|f_{H \rightarrow ff}^{\text{obs}}| = \kappa_f \cdot |f_{H \rightarrow ff}^{\text{SM}}| = \kappa_f \cdot \frac{m_f}{v} \quad f = \mu, \tau, b, t$$

$$\sqrt{\frac{|f_{H \rightarrow VV}^{\text{obs}}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f_{H \rightarrow VV}^{\text{SM}}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \quad V = W, Z$$

Im Rahmen der erzielten Meßgenauigkeit einzigartiges Kopplungsverhalten!

LHC run-2 (Beginn 2014 – Mitte 2015)

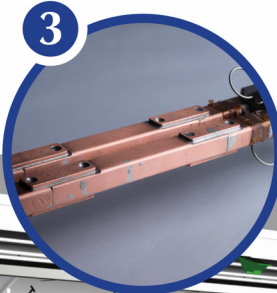
Ouvrir et refermer définitivement 1 695 interconnexions



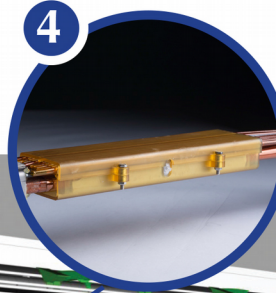
Refaire entièrement 1 500 de ces interconnexions



Consolider les 10 170 interconnexions de 13 kA; installer 27 000 dérivations



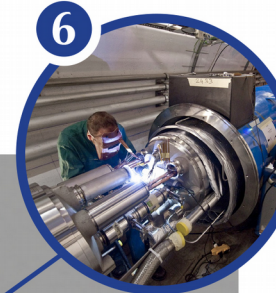
Installer 5 000 systèmes d'isolation électrique consolidés



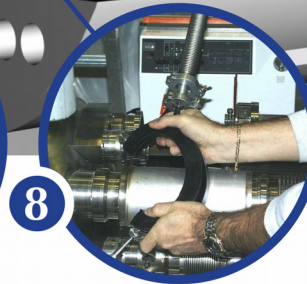
Réaliser 300 000 mesures de la résistance électrique



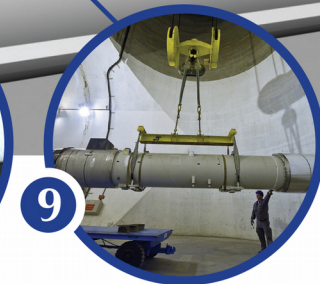
Réaliser 10 170 soudures orbitales de lignes en acier inoxydable



Réaliser 18 000 tests d'assurance qualité électrique



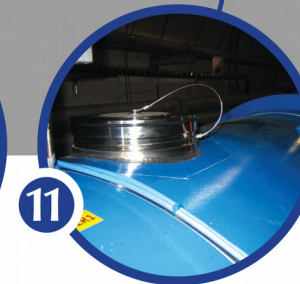
Réaliser 10 170 tests d'étanchéité



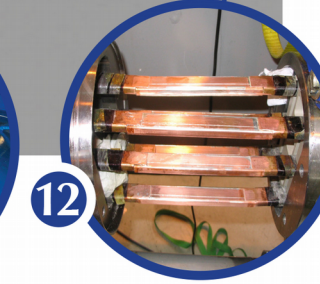
Remplacer 4 quadripôles



Remplacer 15 dipôles



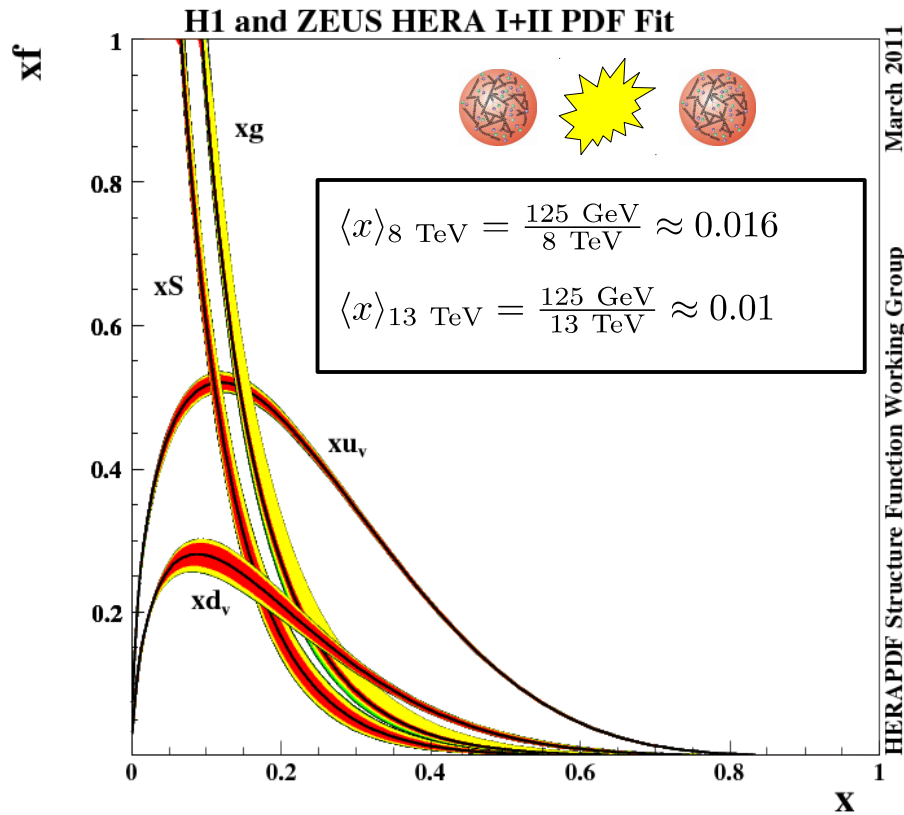
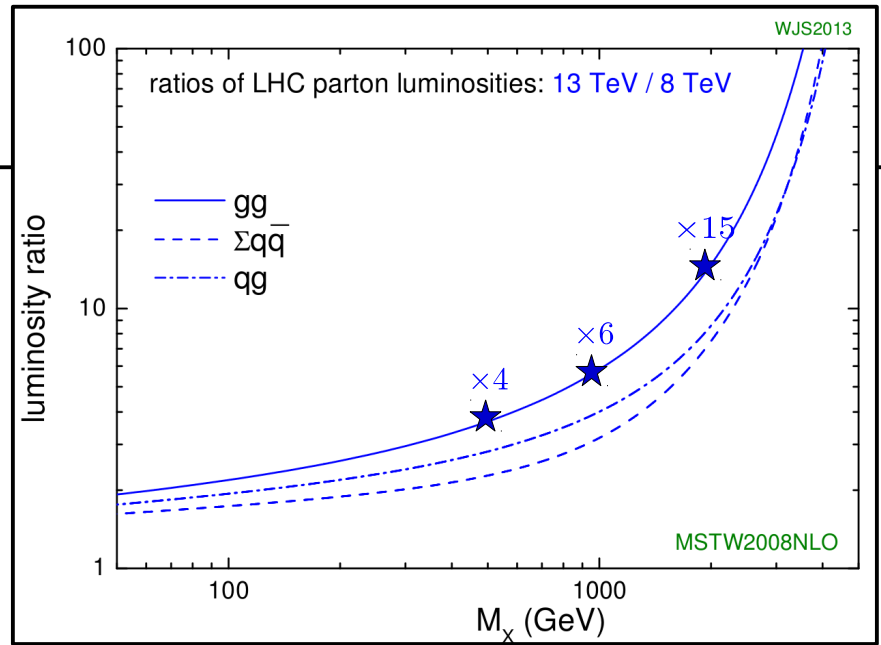
Installer 612 nouvelles soupapes, ce qui porte leur nombre total à 1344



Consolider les circuits de 13 kA dans les 16 boîtiers principaux d'alimentation électrique

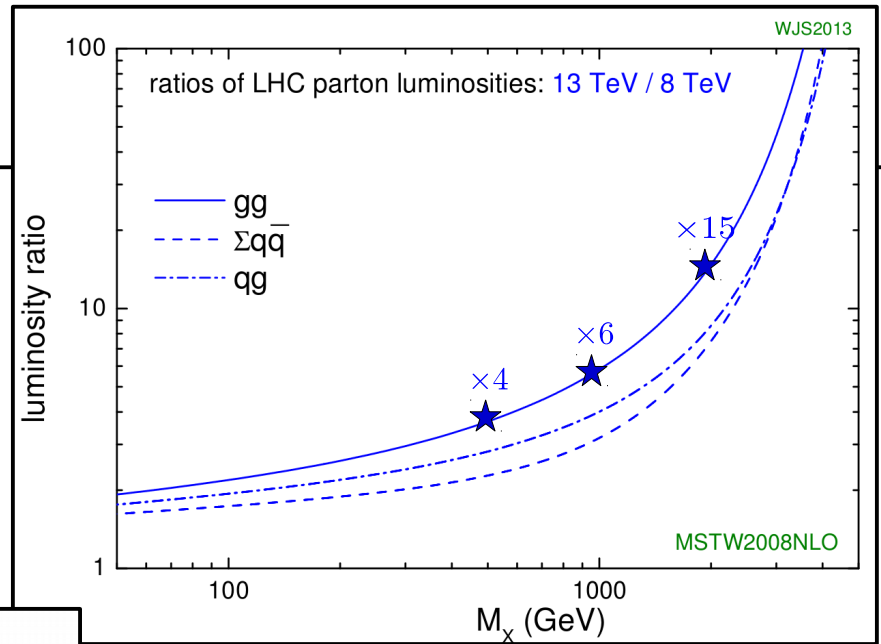
LHC run-1 → run-2

Prozess	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\delta_X/\delta_{h(125)}$
$t\bar{t}$	3.3	1.43
W	1.6	0.70
Z	1.6	0.70
WW	2.0	0.87
$h(125)$	2.3	1.00



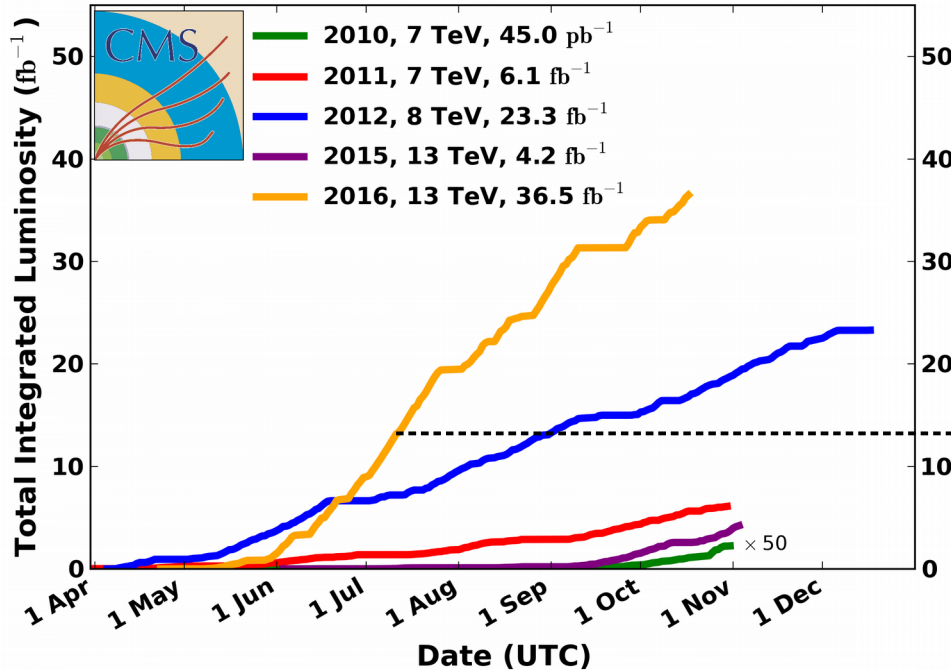
LHC run-1 → run-2

Prozess	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\delta_X/\delta_{h(125)}$
$t\bar{t}$	3.3	1.43
W	1.6	0.70
Z	1.6	0.70
WW	2.0	0.87
$h(125)$	2.3	1.00



CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-10-16 09:05 UTC

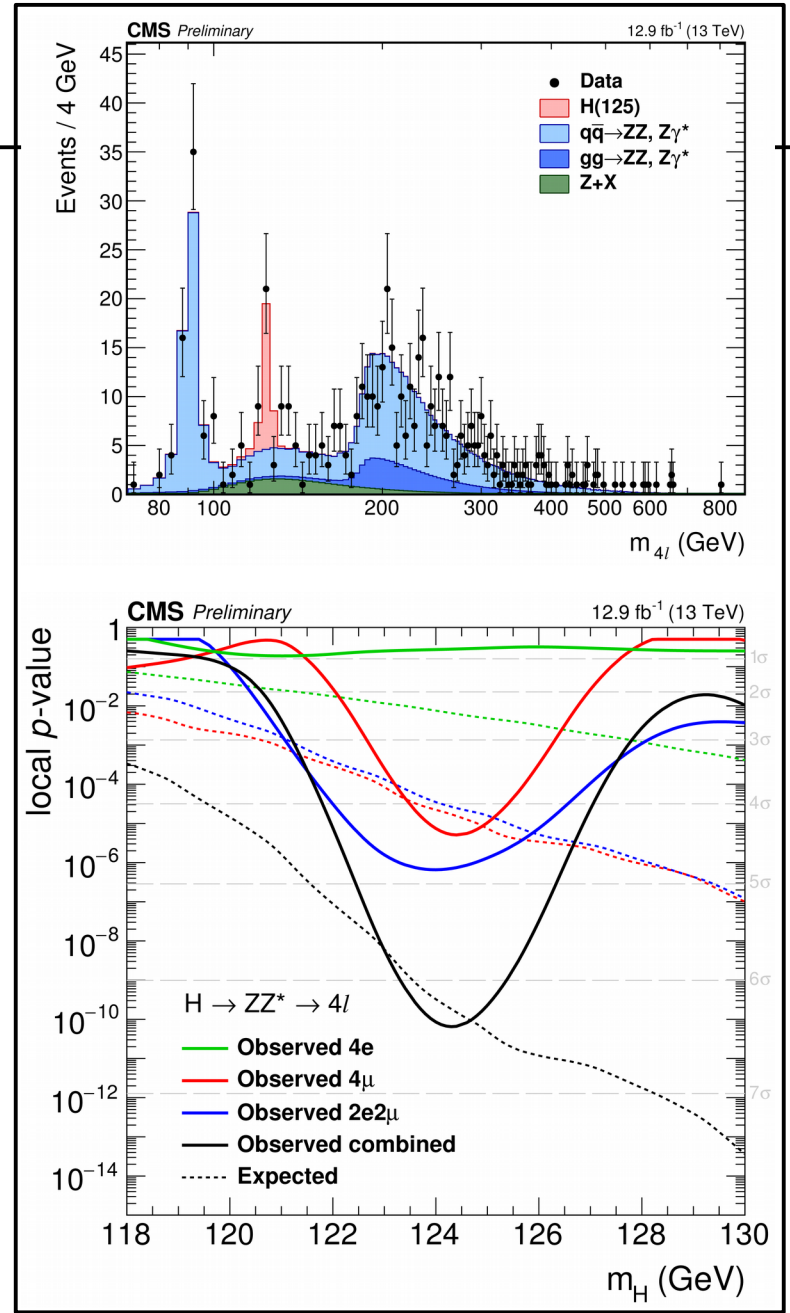
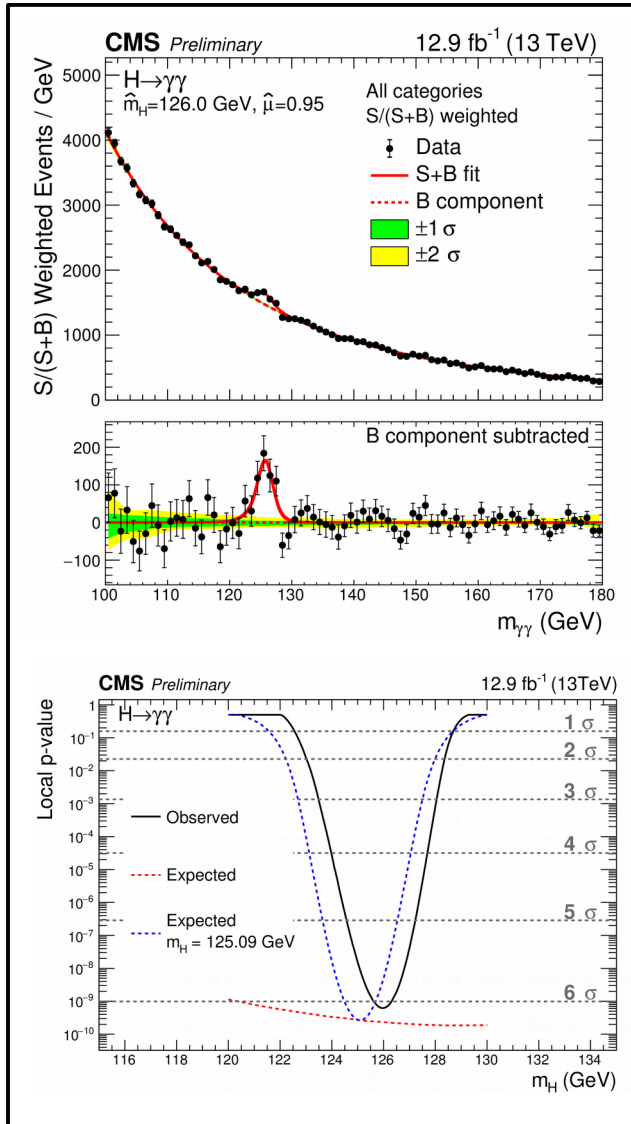


Vorläufige Ergebnisse für ICHEP 2016:

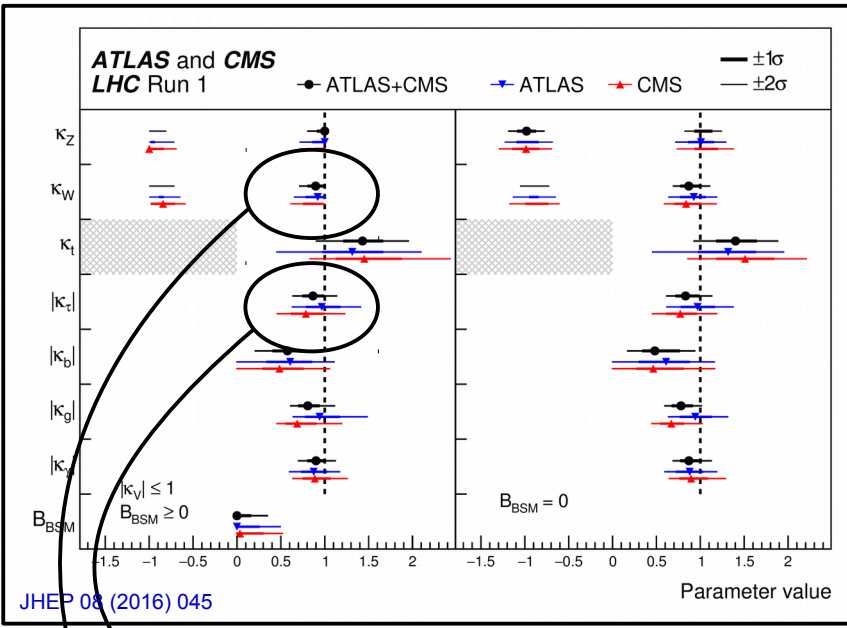
13.2/ fb (ATLAS)

12.9/ fb (CMS)

Higgs Boson noch da?



Raum für neue Physik im Higgs Sektor



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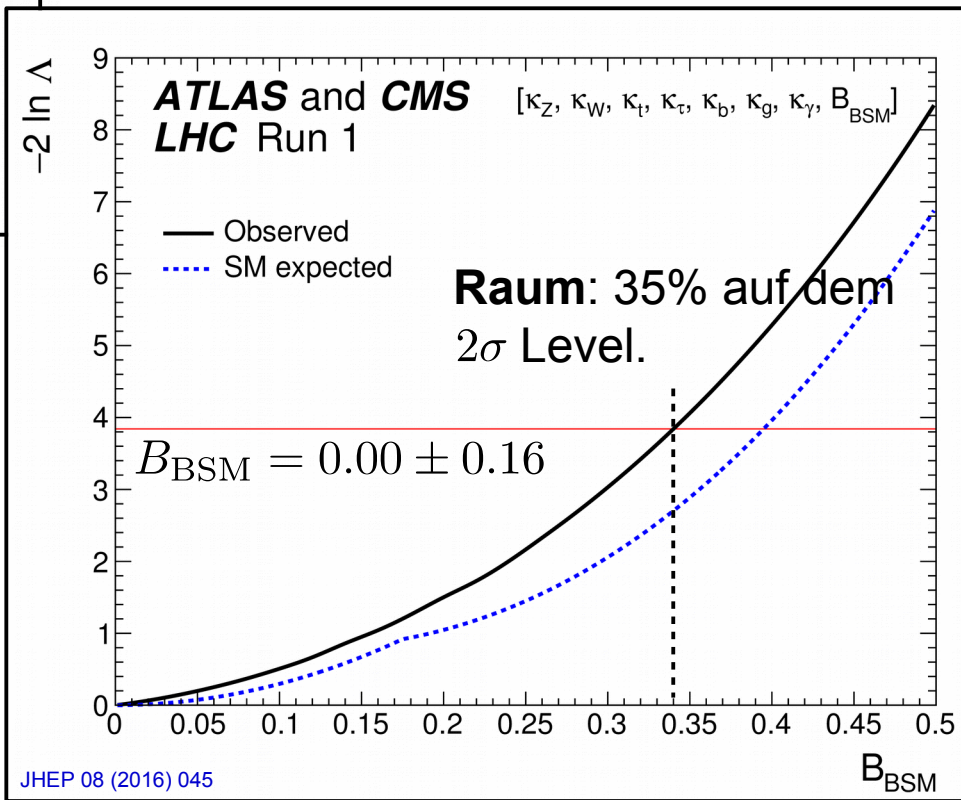
$$\kappa_{\tau} = 0.87 \pm_{0.11}^{0.12}$$

$$\kappa_W = 0.90 \pm 0.09$$

Raum: 20% auf dem 2σ Level.

Zwei Signaturen, um im Higgs Sektor nach neuer Physik zu suchen:

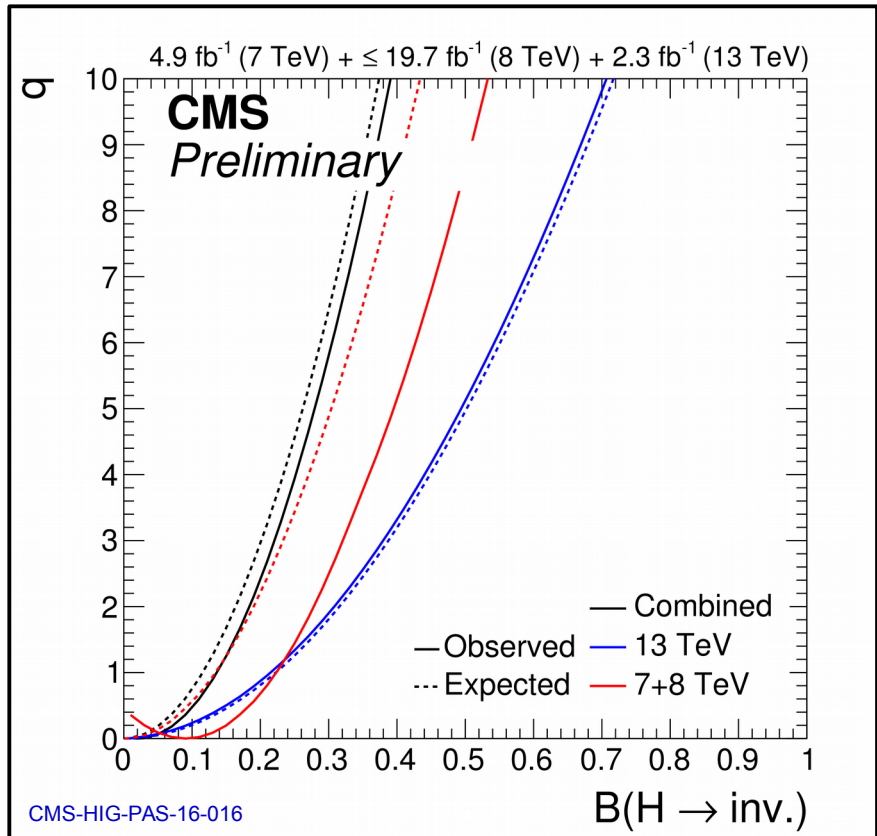
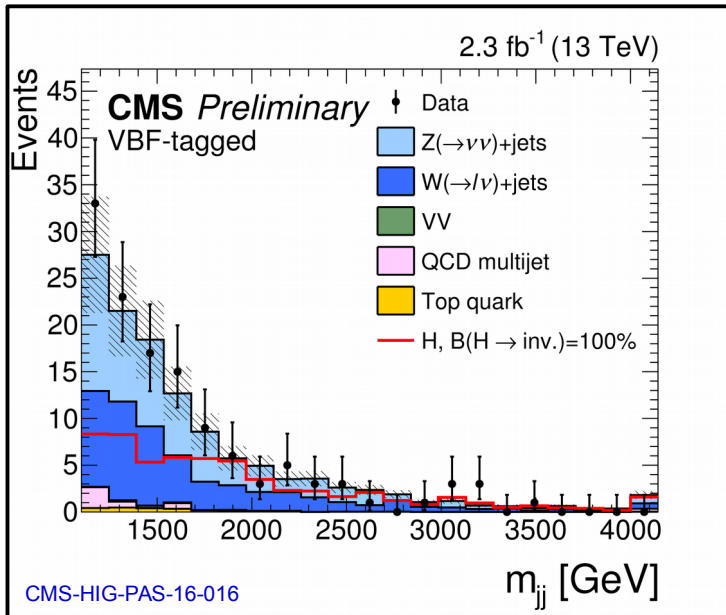
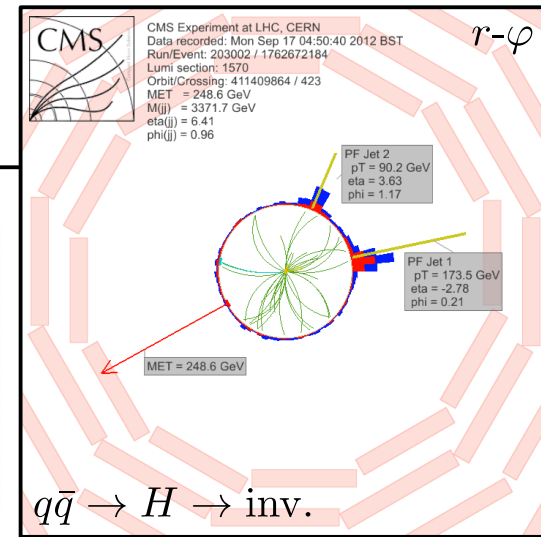
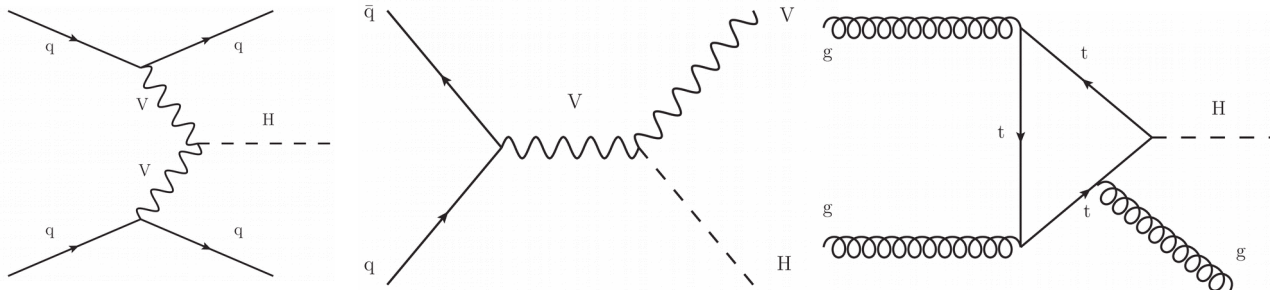
- Direktes Signal eines neuen Teilchens.
- Präsenz neuer Higgs Bosonen führt zu Modifikationen der H(125) Kopplungen.



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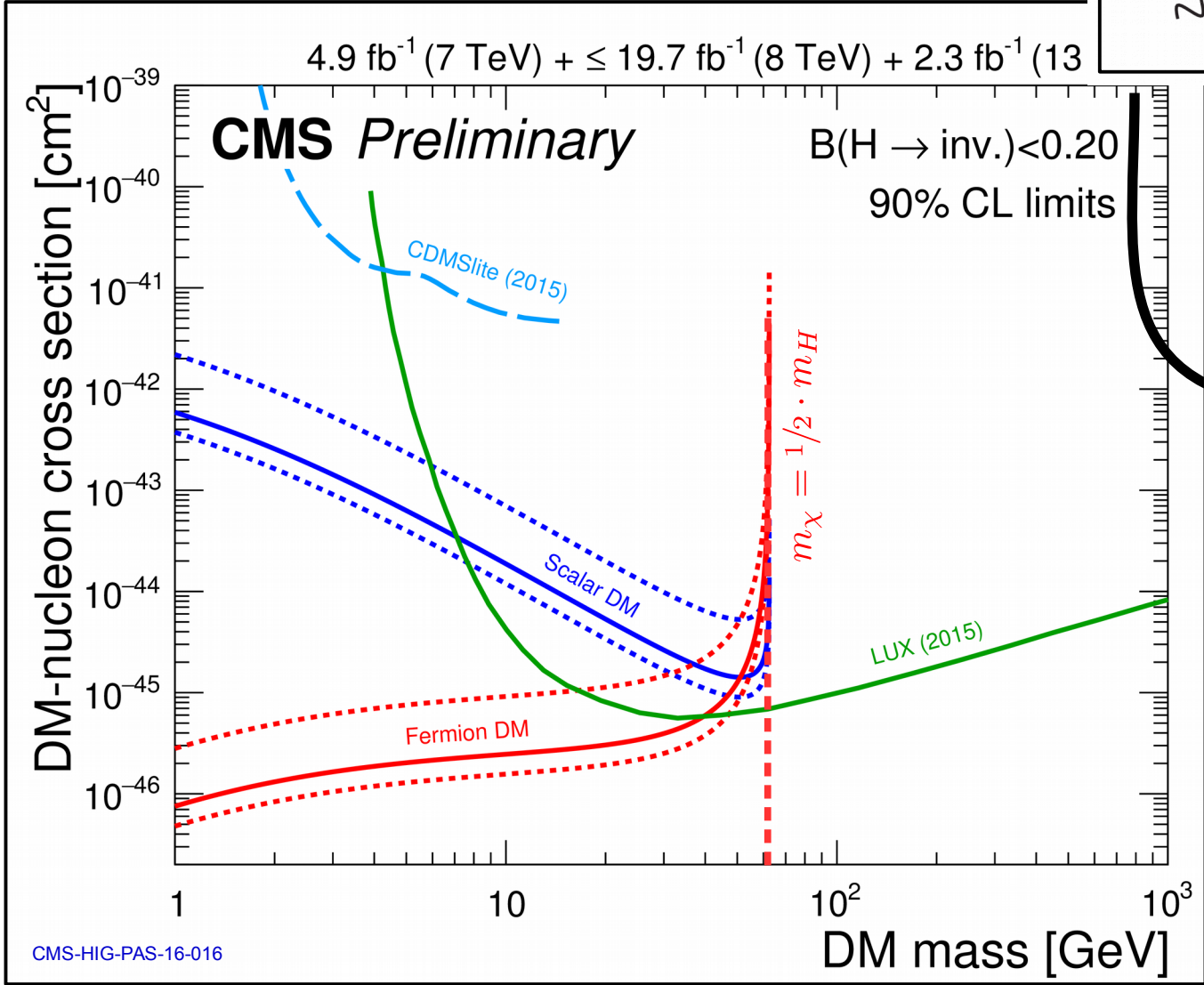
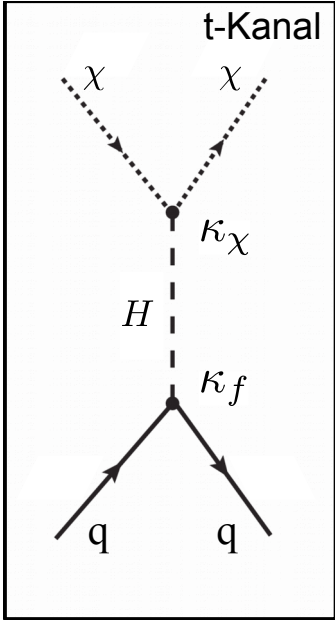
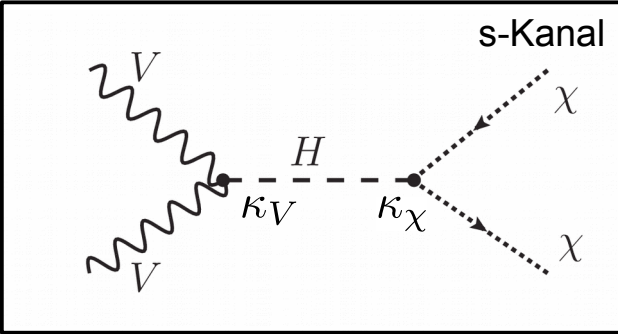
B_{BSM}

Direkte Suche nach $H \rightarrow$ invisible



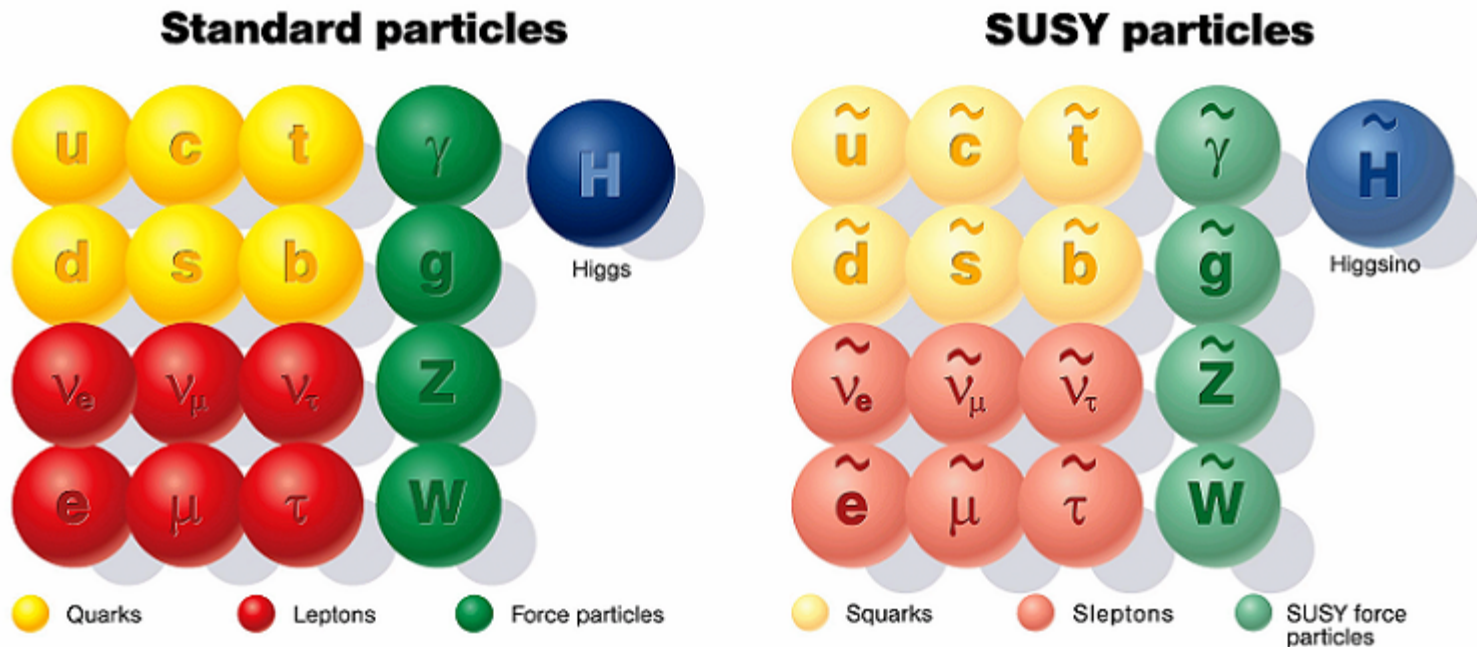
$$BR(H \rightarrow \text{inv}) \leq 0.24(0.23) @ 95\% \text{ CL}$$

Suchen nach Dunkler Materie (DM)



Kandidaten für Dunkel Materie in der Supersymmetrie

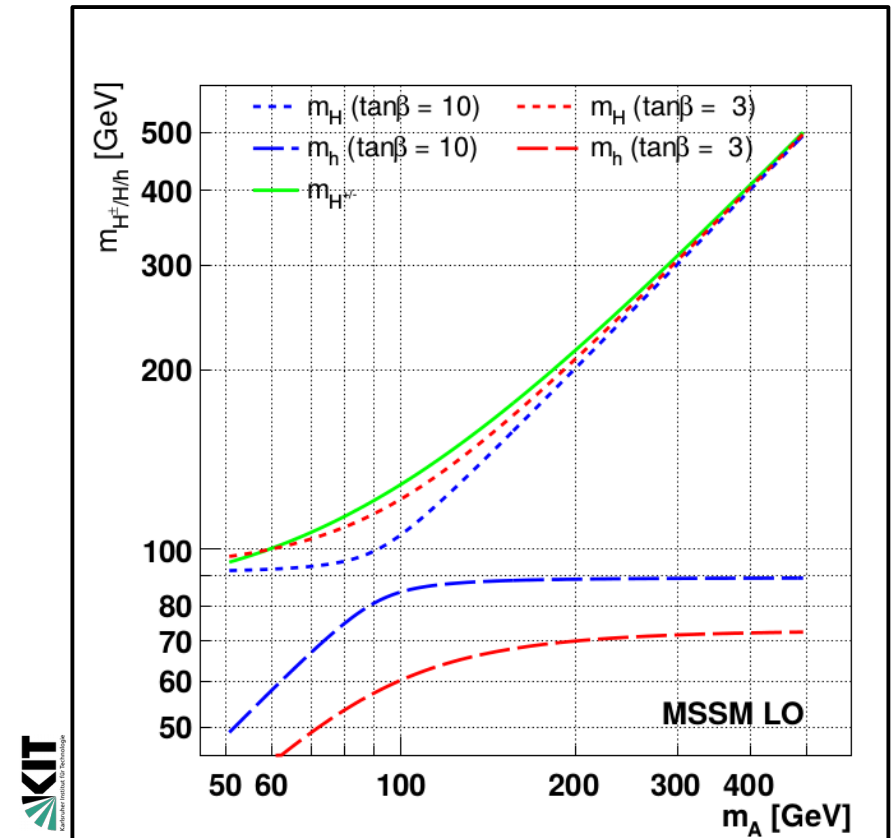
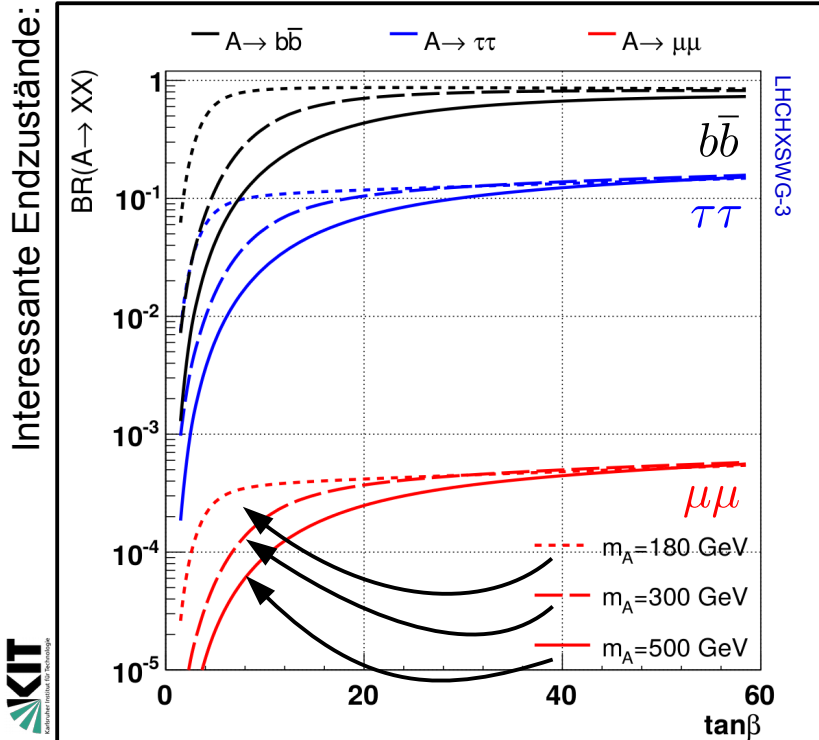
- Erweiterung des SM um eine letzte nicht-triviale Symmetrie Operation (boson \leftrightarrow fermion, Supersymmetrie (SUSY)):



- Löst viele Probleme des Standardmodells.
- Leichtestes SUSY Teilchen perfekter Kandidat für Dunkle Materie.

Higgs Bosonen in der Supersymmetrie

- In supersymmetrischen Modellen erwarten wir fünf(!) Higgs Bosonen: H^\pm , H , h , A
- Strenge Anforderungen an Massenrelationen.
- Nur zwei freie Parameter in führender Ordnung: m_A , $\tan \beta = v_u/v_d$.

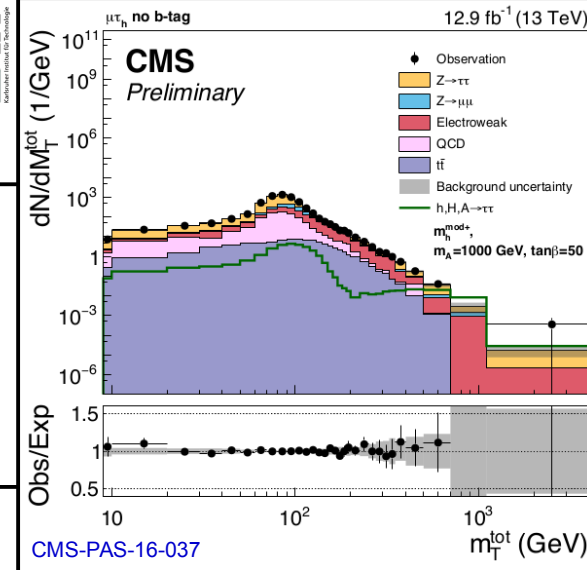
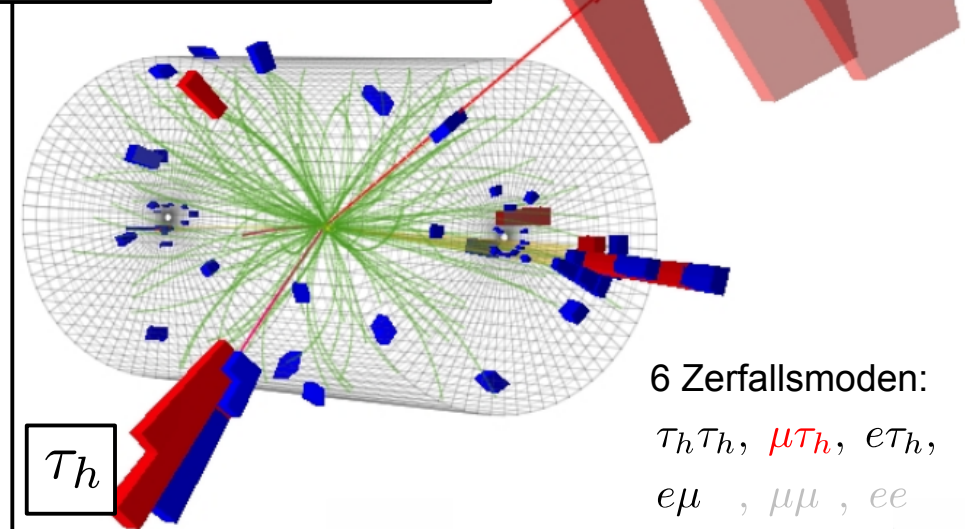
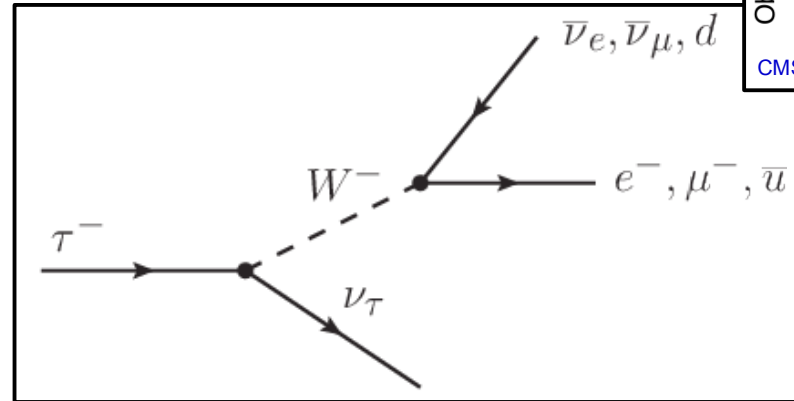


Insbesondere würden solche schwere Higgs Bosonen in b -Quarks und τ -Leptonen zerfallen.

Suche nach $A, H, h \rightarrow \tau\tau$ Zerfällen

τ -Zerfall	BR [%]
$e\nu_e\nu_\tau$	17.83
$\mu\nu_\mu\nu_\tau$	17.41
1-prong ν_τ	37.10
3-prong ν_τ	15.20

- Suche nach zwei isolierten Leptonen im Detektor.
- Reduziere Untergründe durch geeignete Ereignisauswahl.

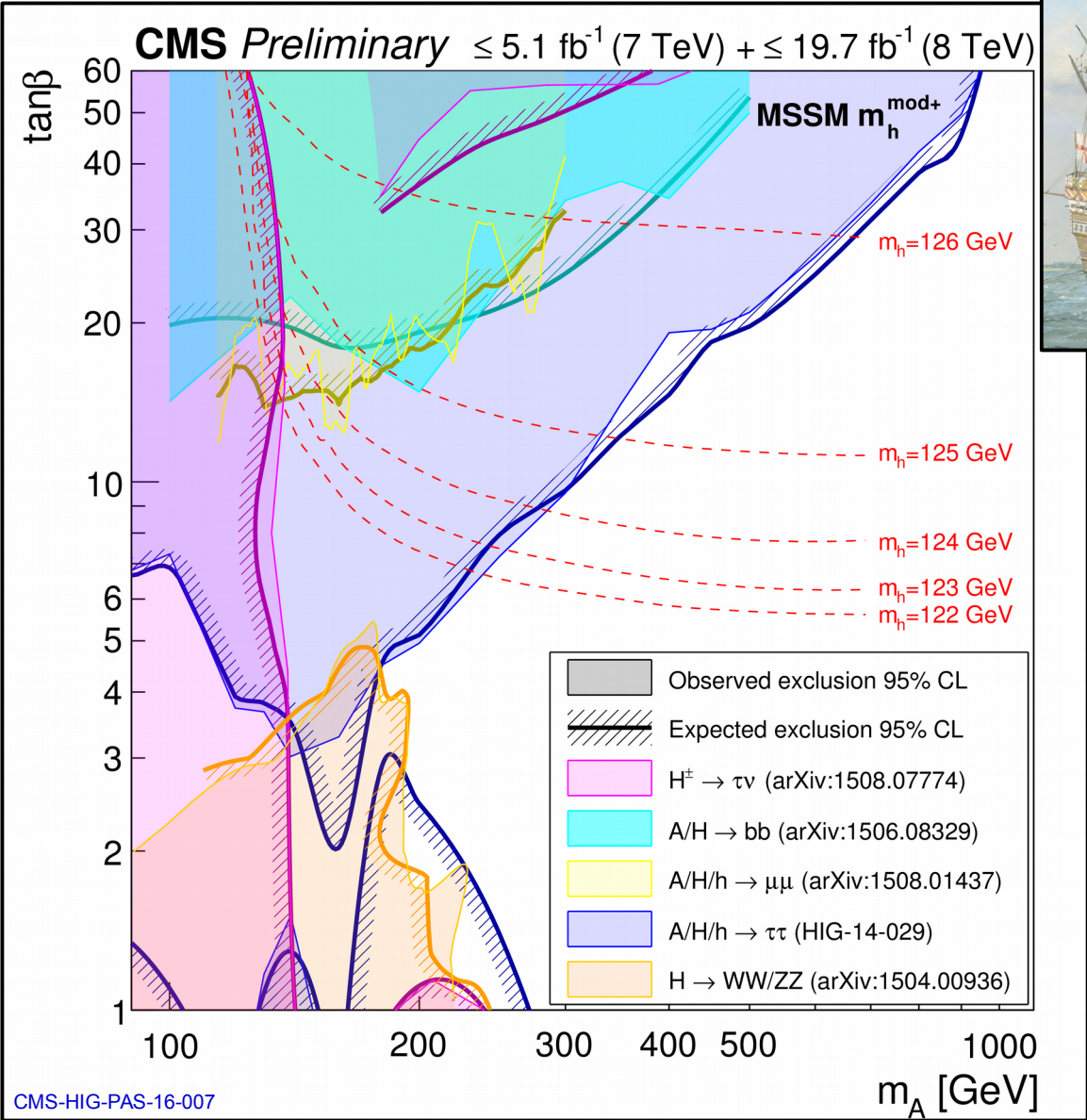


6 Zerfallsmoden:
 $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$,
 $e\mu$, $\mu\mu$, ee

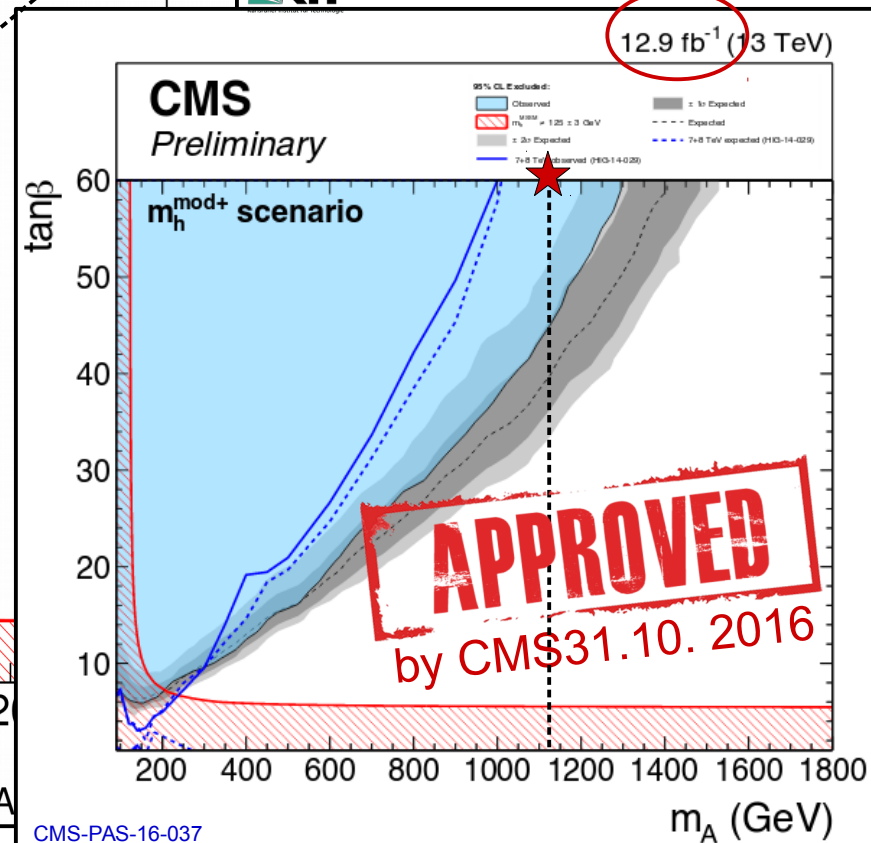
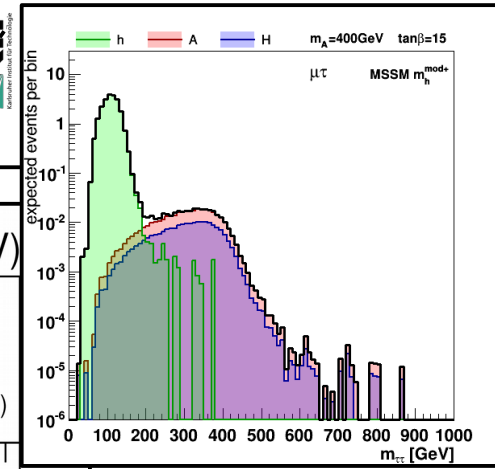
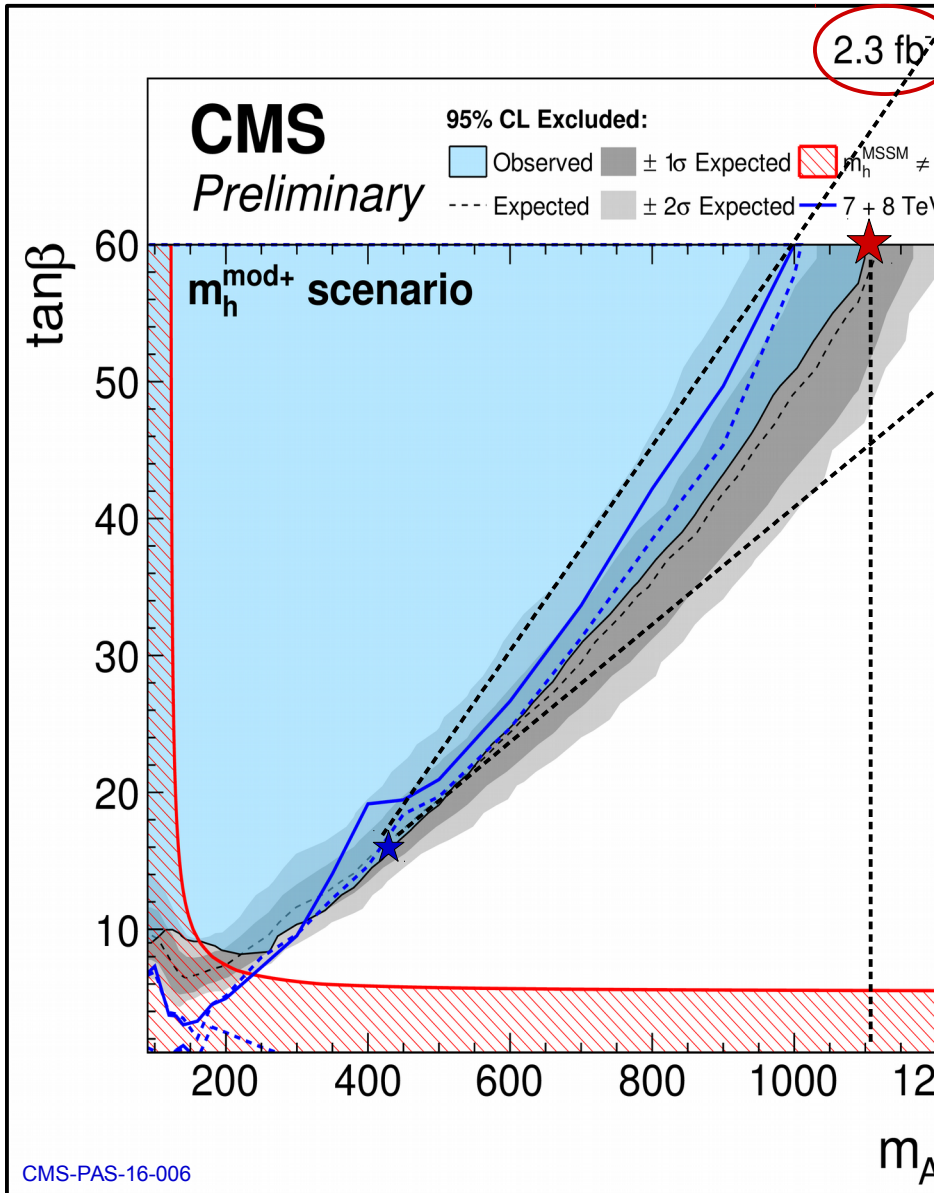
Fazit der LHC run-1 Suchen:



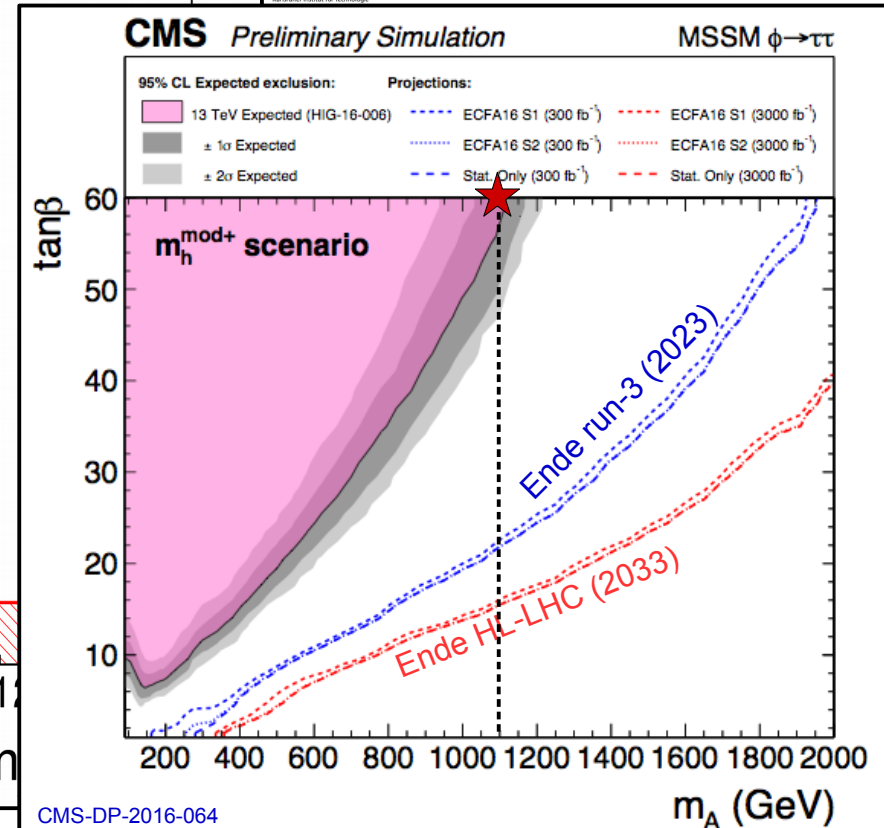
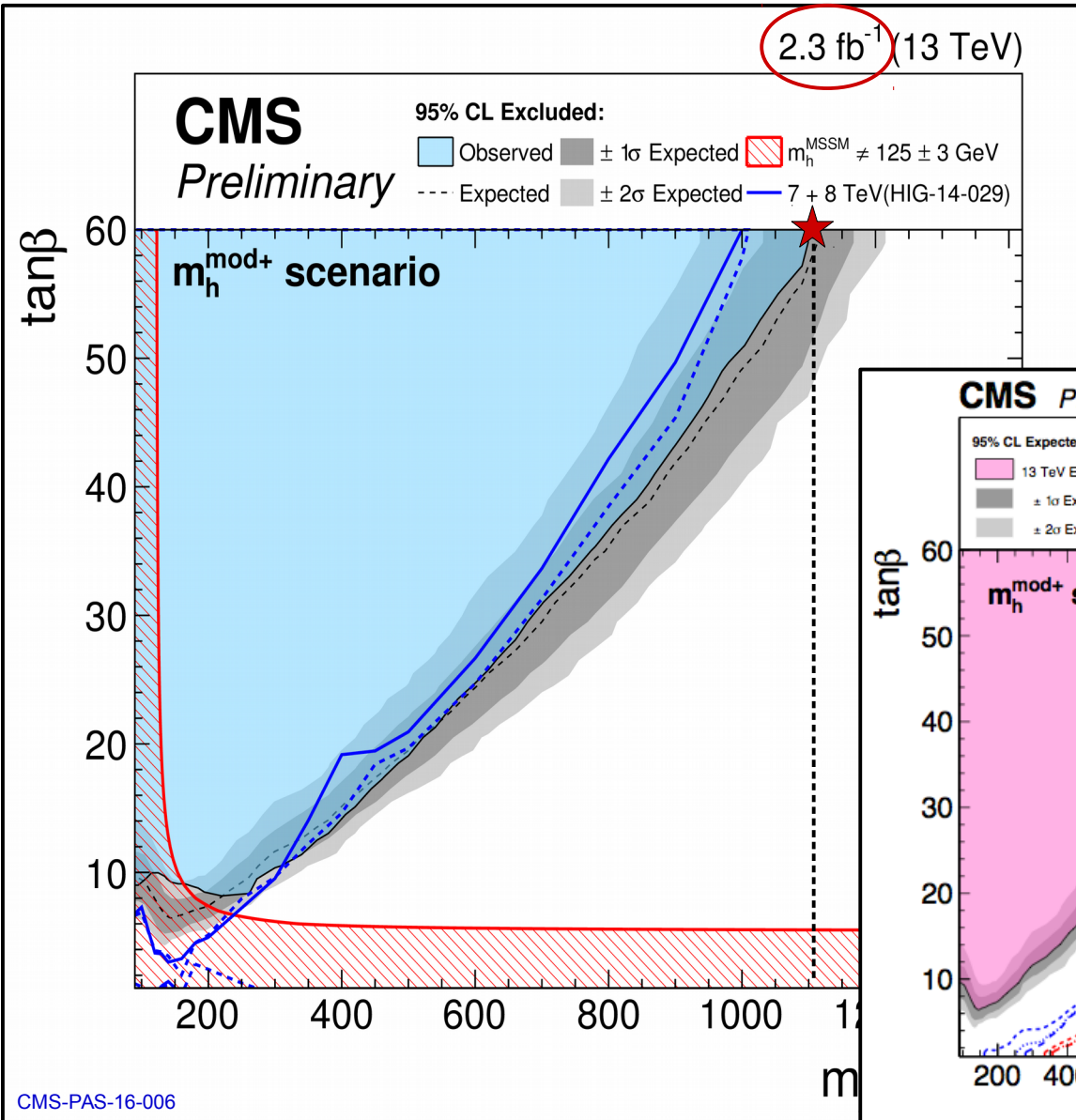
Mary Rose (Flagschiff der englischen Marine 1511 – 1545)



Parameterabdeckung LHC run-2



Blick in die Zukunft...




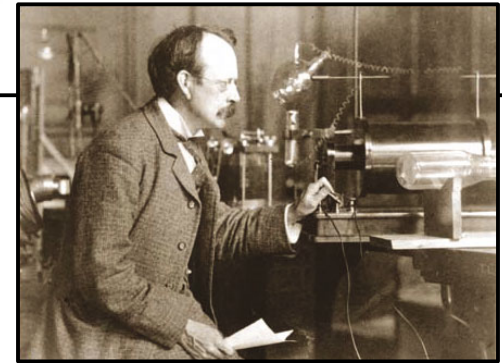
Conclusions

- Die Suche und Entdeckung des Higgs Bosons am LHC ist eine große Erfolgsgeschichte der Teilchenphysik.
- Ein großes Abenteuer seit 2011 an dieser Suche direkt beteiligt zu sein (seit 2013 im Rahmen eines Habilitationsprojektes mit eigener Arbeitsgruppe am KIT).
- Zukünftige Fragen der Higgsphysik/Teilchenphysik:
 - Direkte Suche nach Dunkler Materie an Beschleunigern! → Bezug zur Higgsphysik.
 - Suche nach weiteren Higgs Bosonen, Erweiterungen des Higgs Sektors.
 - Auf zu den Ufern neuer unbekannter Physik!




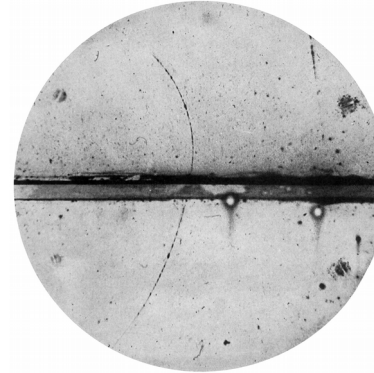
Geschichte der Teilchenphysik

 Discovery of the electron (1897)



























J. J. Thomson (1856 – 1940)


 Discovery of the positron (1932)





C. D. Anderson (1905 – 1991)

-  Relativistic QM (→ Dirac-Equation 1928)
-  Theory of weak IA (→ E. Fermi 1933 – 34)
-  Discovery $\mu^{+/-}$ (→ C. D. Anderson 1937) 
- Discovery $\pi^{+/-}$ (→ C. Powel/G. Occhialini 1947) 
- Discovery π^0 (→ R. Bjorklund et al 1950) 
- Discovery $K^{+/-}$ (→ “V”-particles 1947 – 49) 
- Discovery K^0, Λ^0 (→ “V”-particles 1947) 
- Discovery Σ 's, Ξ 's (→ 1950's) 
- Discovery $\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$ (→ 1952) 

-  Invention of bubble chamber (→ D. Glaser 1952)
-  Observation of ν_e (→ C. Cowan, F. Reines 1956)
-  Observation P violation of weak IA (→ C. Wu, R. Garwin 1956)
-  Gauge field theory of weak IA (→ S. Glashow, S. Weinberg 1961)
-  Observation of ν_μ (→ L. Lederman, M. Schwartz, J. Steinberger 1962)
-  Observation CP violation of weak IA (→ J. Cronin, V. Fitch 1964)
-  Discovery J/ψ 's (→ B. Richter, S. Thing, 1974) 
- Discovery Υ 's (→ L. Lederman, E288 collaboration, 1977) 
-  Discovery of W, Z (→ UA1 & UA2 collaboration, 1983) 
- Observation of t (→ CDF & D0 collaboration 1995) 
-  Observation of ν_τ (→ DONUT collaboration 2000)
-  Discovery of H (→ ATLAS & CMS collaboration 2012)

 Overall $\mathcal{O}(30)$ Nobel prizes in physics went to directly particle physics related topics.

- Ungefähr so alt wie der Nobelpreis.
- Entdecker boom um 1930er – 40er Jahre.
- Seit Bestehen etwa jeder vierte Nobelpreis in die Teilchenphysik.

 discovered in airshower experiments
 discovered in collider experiments

Leptonen:

ν_e μ^- e^- ν_τ τ^-
 ν_μ

Hadronen:

Mesonen: J/ψ π^- D^0 B^- η
 η' ϕ K^{*-} ρ^0
 η_c B^+
 ω π^+ ρ^- π^0 ρ^+ η_b Δ^{++}
 D_s^- D_s^+ K^{*+} K^+ Υ Δ^-
 K^{*0} D_s^{*-} K_S^0 K_L^0 K^- D^{*+} Σ_b^- Σ_b^+ Δ^0
 D^- B_c^{*-} B_c^+ B_c^0 B_c^{*+} D^{*-} D^+ Δ^+ Σ_b^0 Σ_b^+ Δ^0 Ξ_b^{*+} Ξ_b^{*++} Ξ_c^{*+} Ξ_c^{*++}
 D^{*0} B_c^{*0} B_c^- B_s^+ B_s^0 B^{*+} Ξ_b^- Ξ_b^0 Ξ_c^+ Ξ_c^0 Ξ_b^{*+} Ξ_b^{*0} Ξ_c^{*+} Ξ_c^{*0}
 B_c^- B_s^+ B_s^0 B^{*+} Ω_b^- Ω_c^0 Ξ_b^{*+} Ξ_b^{*0} Ξ_c^{*+} Ξ_c^{*0}
 B_c^- B_s^+ B_s^0 B^{*+} Δ^+ Ω_{cb}^0 Σ_c^{*0} Ω_{cc}^+ Ω_{ccb}^+ Σ_c^{*+} Ξ_b^{*0} Ξ_c^{*0}
 Ω_{cb}^0 Σ_c^{*0} Ω_{cc}^+ Ω_{ccb}^+ Σ_c^{*+} Ξ_b^{*0} Ξ_c^{*0}

Baryonen:

Ω_{bbb}^{++} Ξ_c^+
 Σ^0 Ω_{ccc}^{++} Ω_{cbb}^{*0} Ω_{bb}^{*-}
 p n Ω_{ccb}^{*+} Σ^+ Ξ^- Ω_{ccc}^{++} Ω_{cbb}^{*0} Ω_{bb}^{*-}
 Δ^{++} Ω_{ccb}^{*+} Σ^+ Ξ^- Ξ^0 $\Xi_{cb}^{\prime 0}$ Ω_c^{*0} Λ^0
 Λ_b^+ Δ^{++} Ω_{ccb}^{*+} Σ^+ Ξ^- Ξ^0 $\Xi_{cb}^{\prime 0}$ Ω_c^{*0} Λ^0
 Λ_c^+ $\Xi_{bb}^{\prime -}$ $\Xi_{cb}^{\prime +}$ Ω_b^{*-} Σ^- Ξ^0 $\Xi_{cb}^{\prime 0}$ Ω_c^{*0} Λ^0
 Δ^- Σ_b^{*+} Δ^+ Δ^- Σ_c^+ Ξ^{*0} Ω_{cb}^{*0} Ω_c^{*+} Ω_c^{*+}
 Σ_b^- Σ_b^+ Δ^0 Ξ_{cb}^{*0} Σ_c^{++} Ξ_b^{*0} Ξ_{cb}^+ Ξ_b^{*0} Ξ_c^0
 Δ^0 Σ_b^+ Σ_b^0 Ξ_{cb}^{*+} $\Xi_{cb}^{\prime +}$ Ξ_c^0 Ξ_{cb}^0 Ξ_c^0 Ξ_b^{*-}
 Ξ_b^- Ξ_b^0 Ξ_{cc}^+ Ξ_{cc}^{*+} Ξ_c^+ $\Xi_{bb}^{\prime 0}$ Σ_b^{*-} Σ_c^0 Ξ_{bb}^{*-}
 Ω_b^- Ω_c^0 Ξ_{cb}^{*+} $\Xi_b^{\prime -}$ Ξ_{cc}^{*++} $\Xi_{bb}^{\prime 0}$ Σ_b^{*-} Σ_c^0 Ξ_{bb}^{*-}
 Δ^+ Ω_{cb}^0 Σ_c^{*-} Ω_{ccb}^+ Σ_c^{*+} Ω_{cbb}^0 Σ_b^{*0} Ξ_c^{*+}
 Ω_{cb}^0 Σ_c^{*0} Ω_{cc}^+ Ω_{ccb}^+ Σ_c^{*+} $\Xi_b^{\prime 0}$ Ξ_c^{*0}
 Σ_c^{*0} Ω_{cc}^+ Σ_c^{*++} Σ_c^{*0} Ξ_c^{*+}

+150 weitere bekannte Meson Anregungszustände.

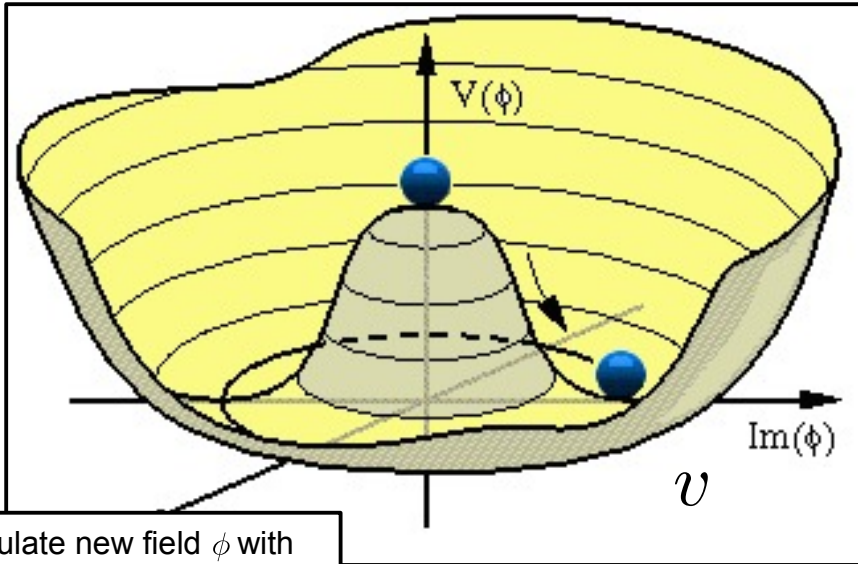
+152 weitere bekannte Baryon Anregungszustände.

$\mathcal{O}(400)$ bekannte Elementarteilchen.

$$J^P = 0^- \quad J^P = 1^- \quad J^P = 1/2^+ \quad J^P = 3/2^+$$

How can $SU(2)_L$ symmetry be the source of weak interactions while at the same time all interacting particles with $m \neq 0$ explicitly break this symmetry?!?

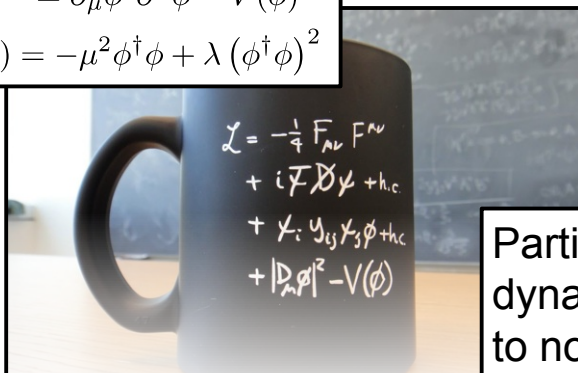
Spontaneous symmetry breaking:



Postulate new field ϕ with symmetry breaking vacuum:

$$\mathcal{L}^{\text{Higgs}} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Lagrangian Density of (baryonic)

Particle masses created dynamically by coupling to non-zero vacuum.

$$y_e \left(v + \frac{H}{\sqrt{2}} \right) \bar{e} e \quad m_e = y_e \cdot v$$

- Symmetry inherent to the system but not to its energy ground state (\rightarrow quantum vacuum).
- Excitation of vacuum ground state leads to existence of a new particle, characterized by very peculiar coupling structure, needed to preserve the symmetry of the system:

$$f_{H \rightarrow ff} = i \frac{m_f}{v} \quad (\text{Fermions})$$

$$f_{H \rightarrow VV} = i \frac{2m_V^2}{v} \quad (\text{Heavy Bosons trilinear})$$

$$f_{HH \rightarrow VV} = i \frac{2m_V^2}{v^2} \quad (\text{Heavy Bosons quartic})$$

$$f_{H \rightarrow HH} = i \frac{3m_H^2}{v} \quad (H \text{ Boson trilinear})$$

$$f_{HH \rightarrow HH} = i \frac{3m_H^2}{v^2} \quad (H \text{ Boson quartic})$$