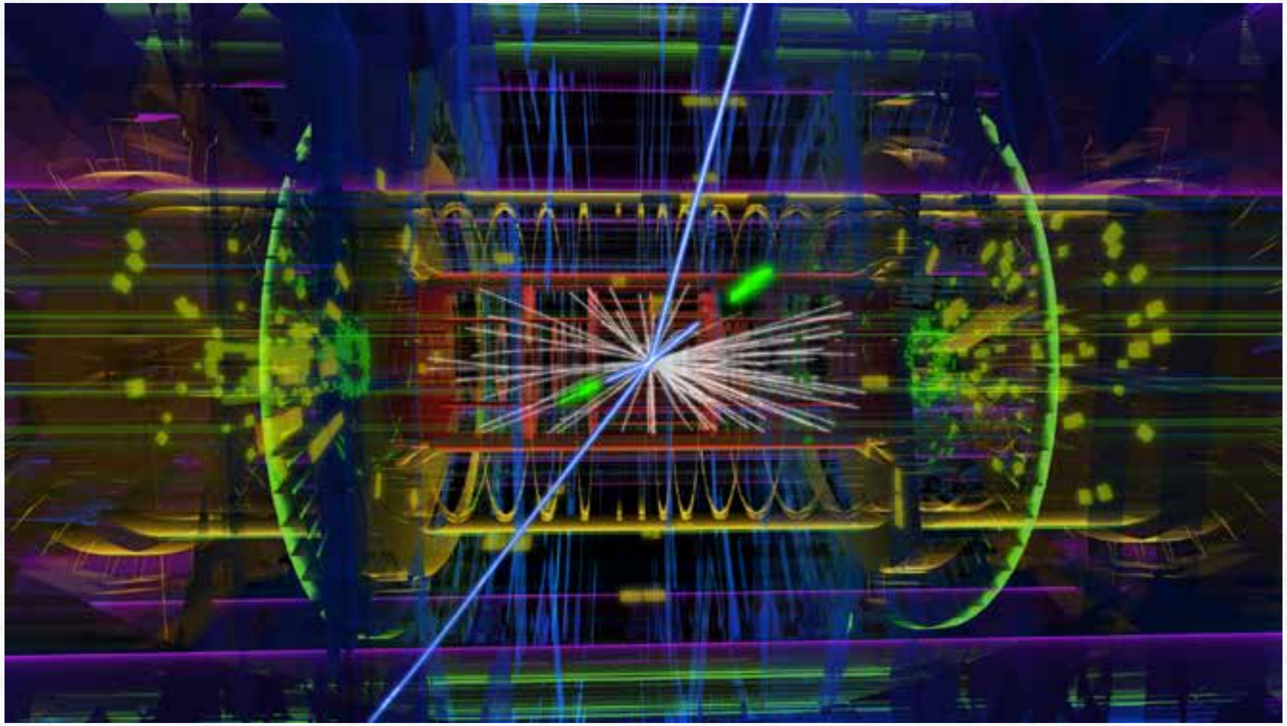
Die Entdeckung des Higgs-Teilchens am CERN



Prof. Karl Jakobs
Physikalisches Institut
Universität Freiburg

From the editorial:

"The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers."

Nobel-Preis für Physik 2013:   François Englert und Peter Higgs

“ … for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of sub-atomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider.”

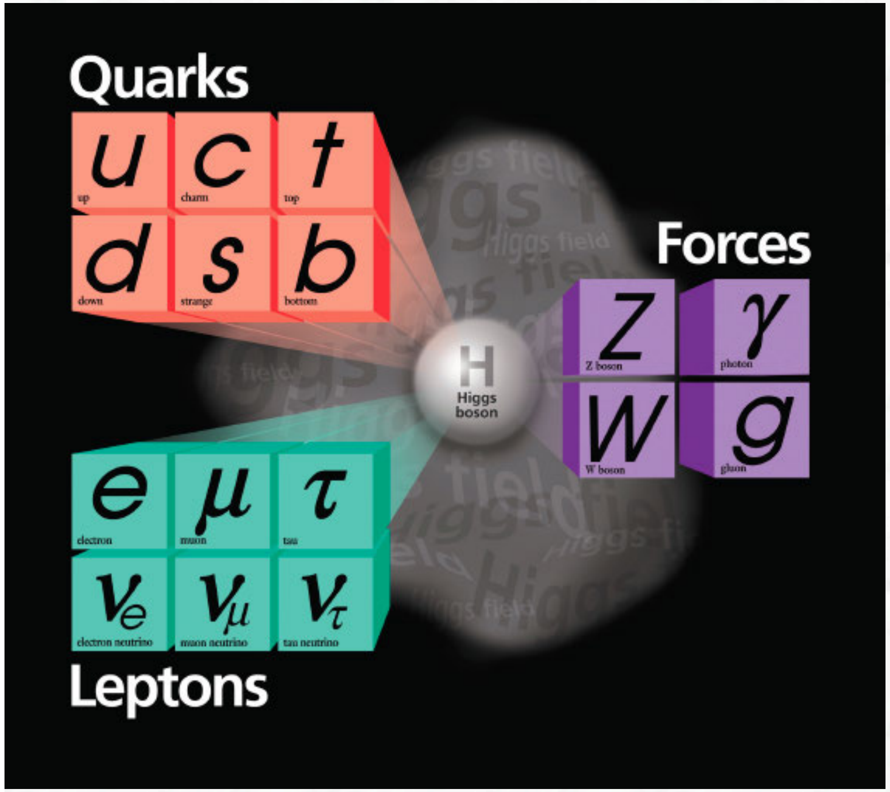
EPS Prize 2013:

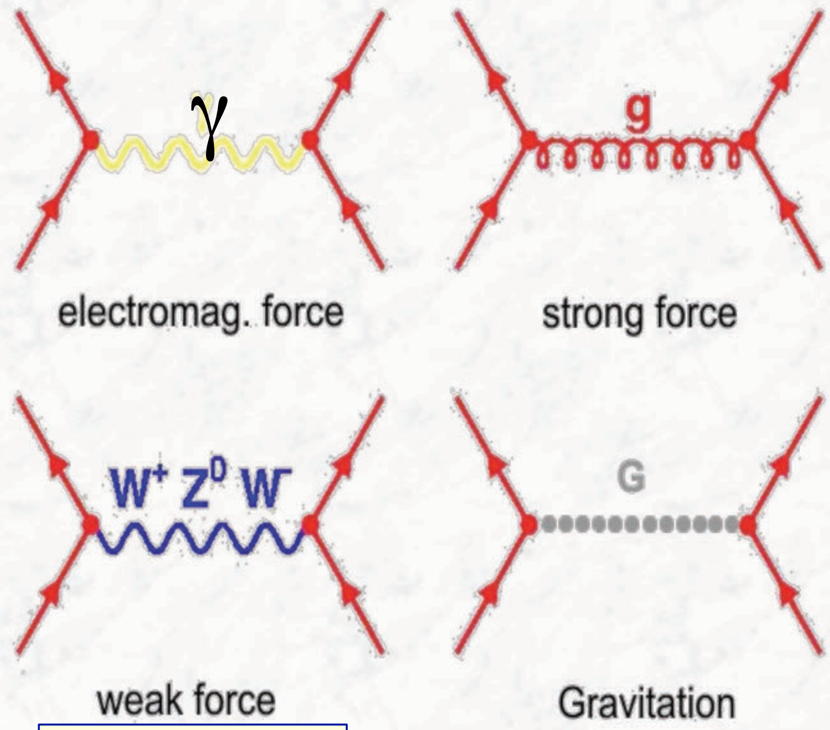
The 2013 High Energy and Particle Physics Prize, for an outstanding contribution to High Energy Physics, is awarded to the ATLAS and CMS collaborations, "for the discovery of a Higgs boson, as predicted by the Brout-Englert-Higgs mechanism", and to Michel Della Negra, Peter Jenni, and Tejinder Virdee, "for their pioneering and outstanding leadership rôles in the making of the ATLAS and CMS experiments".

Physik-Journal Februar 2015:

“.. Obwohl in diesen großen Kollaborationen eine große Zahl von Forschern mitarbeitet, ist es möglich, einzelne Forscherpersönlichkeiten herauszuheben, deren Ideen und Arbeit für den Erfolg des Experiments von besonderer Bedeutung waren. Zu diesen gehört neben den Sprechern der Experimente Karl Jakobs.”

The Standard Model of Particle Physics





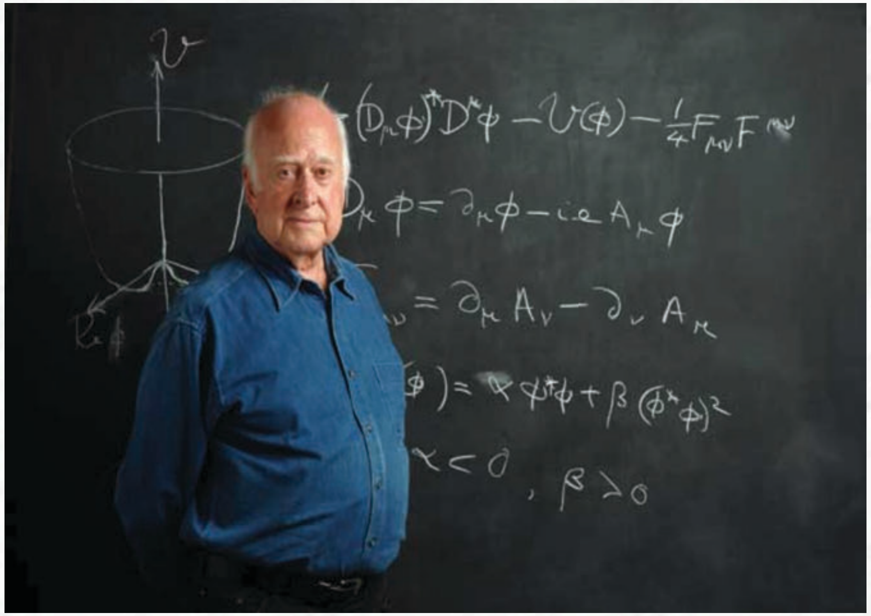
$m_W \approx 80.4$ GeV
$m_Z \approx 91.2$ GeV

(i) Matter particles: quarks and leptons (spin ½, fermions)

(ii) Four fundamental forces: described by quantum field theories (except gravitation)
→ massless spin-1 gauge bosons

(iii) The Higgs field → scalar field, spin-0 Higgs boson

The Brout-Englert-Higgs Mechanism



F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

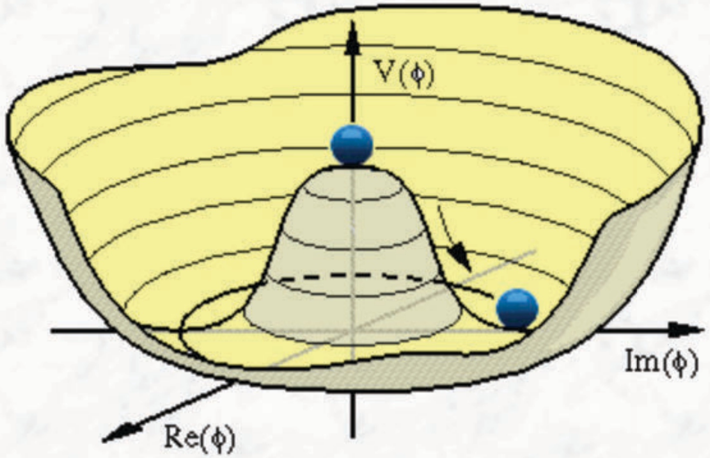
The Brout-Englert-Higgs Mechanism

R. Brout (1964)

P. Higgs (1964)

F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

The Brout-Englert-Higgs Mechanism



Complex scalar (spin 0) field ϕ with potential:

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

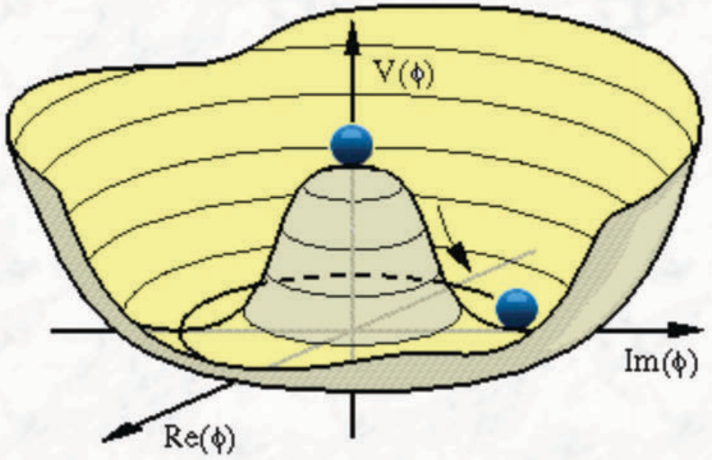
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H <$ ~1000 GeV)

→ Particles acquire mass through interaction with the Higgs field

The Brout-Englert-Higgs Mechanism



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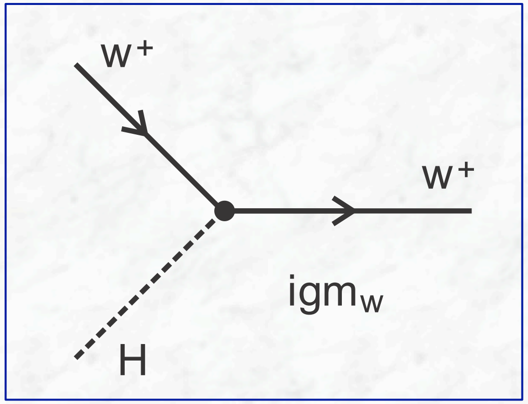
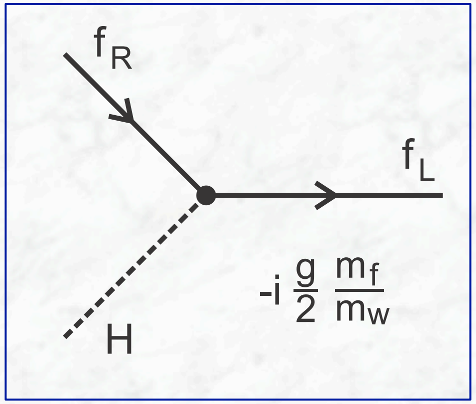




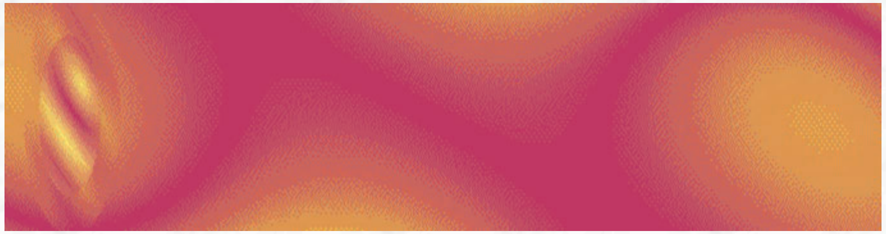
- Couplings proportional to mass

Prinzip der Massenerzeugung

Leeres Vakuum
Alle Teilchen sind masselos und bewegen sich mit derselben Geschwindigkeit, der Lichtgeschwindigkeit.

Higgs-Feld
Teilchen wechselwirken mit dem Higgs-Feld und bewegen sich langsamer. Sie erhalten effektiv eine Masse. Die Masse hängt von der Stärke der Wechselwirkung mit dem Higgs-Feld ab.

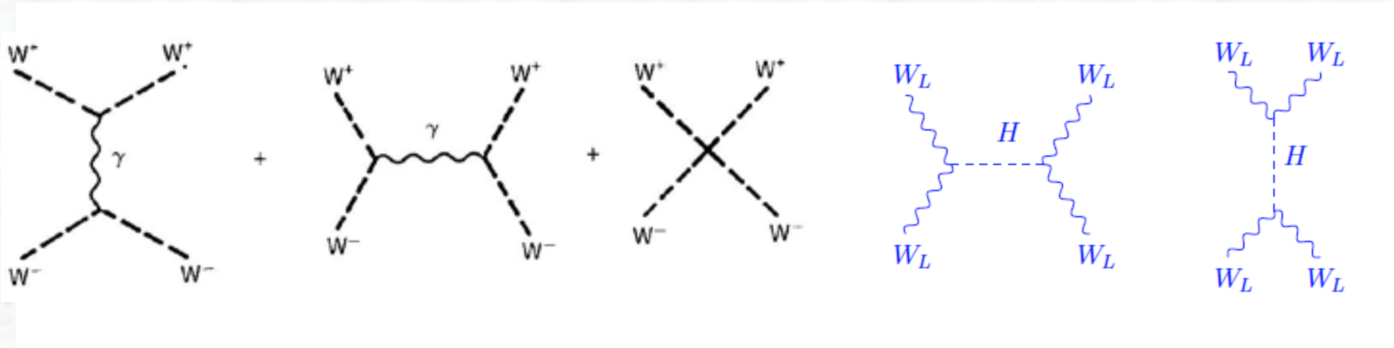
Das Higgs-Teilchen: Anregung des Higgs-Feldes



The Higgs field solves two fundamental problems:

(i) Masses of the vector bosons W and Z and fermions

(ii) Divergences in the theory (scattering of W bosons)
("Ultraviolet regulator")

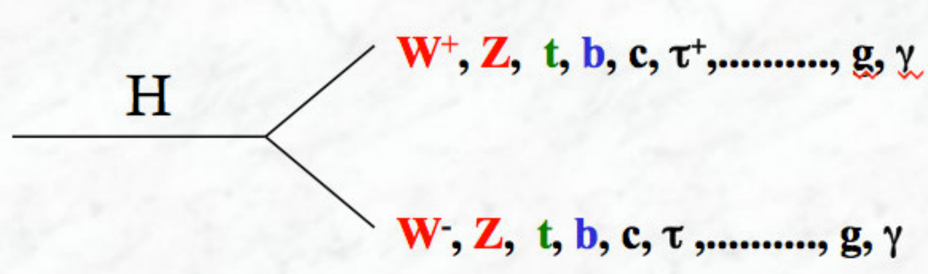


$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$ (no Higgs boson)

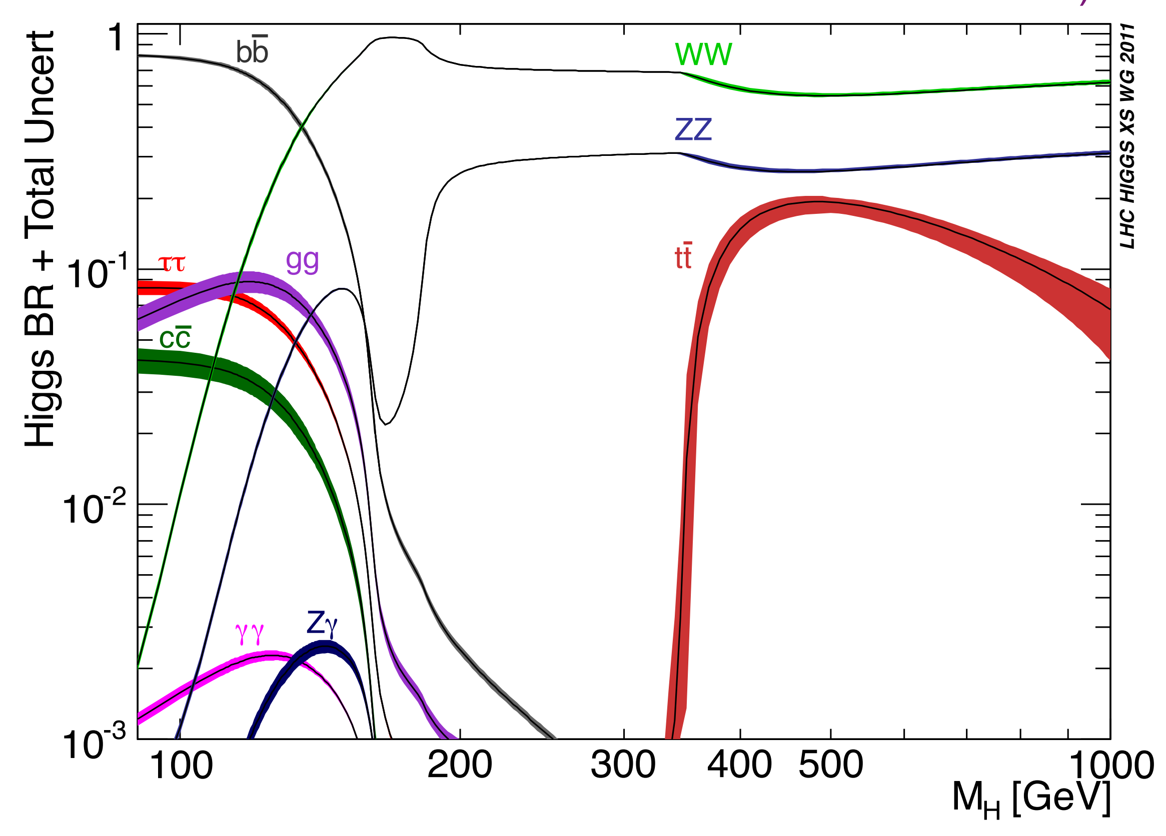
$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$ (with Higgs boson)

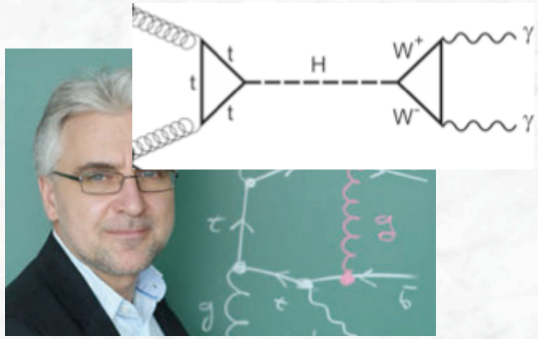
Higgs Boson Decays

- The Higgs boson decays rapidly (10^{-22} s) into kinematically accessible particles



*)



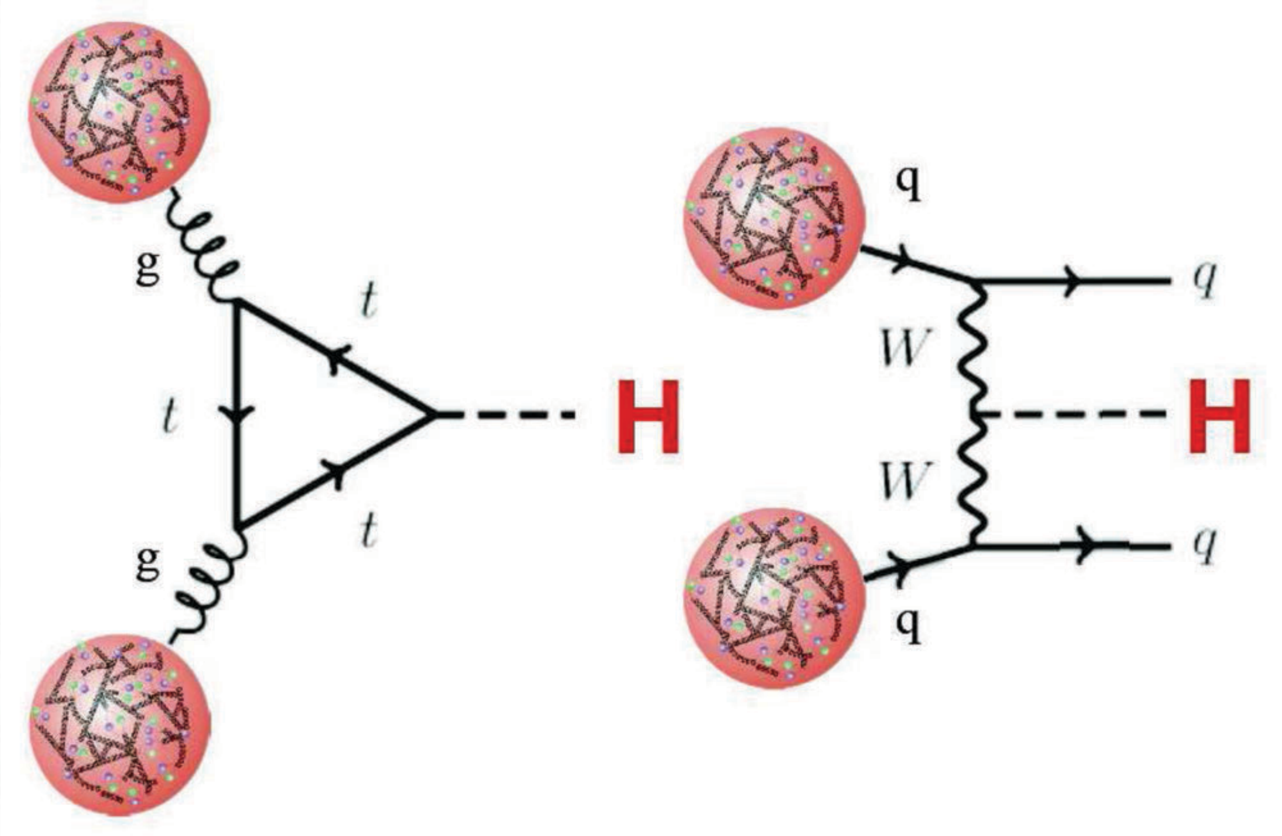


Stefan Dittmaier
Working group convenor (2010-2012)

Markus Schumacher
ATLAS representative (seit 2014)

*) LHC Higgs cross-section working group

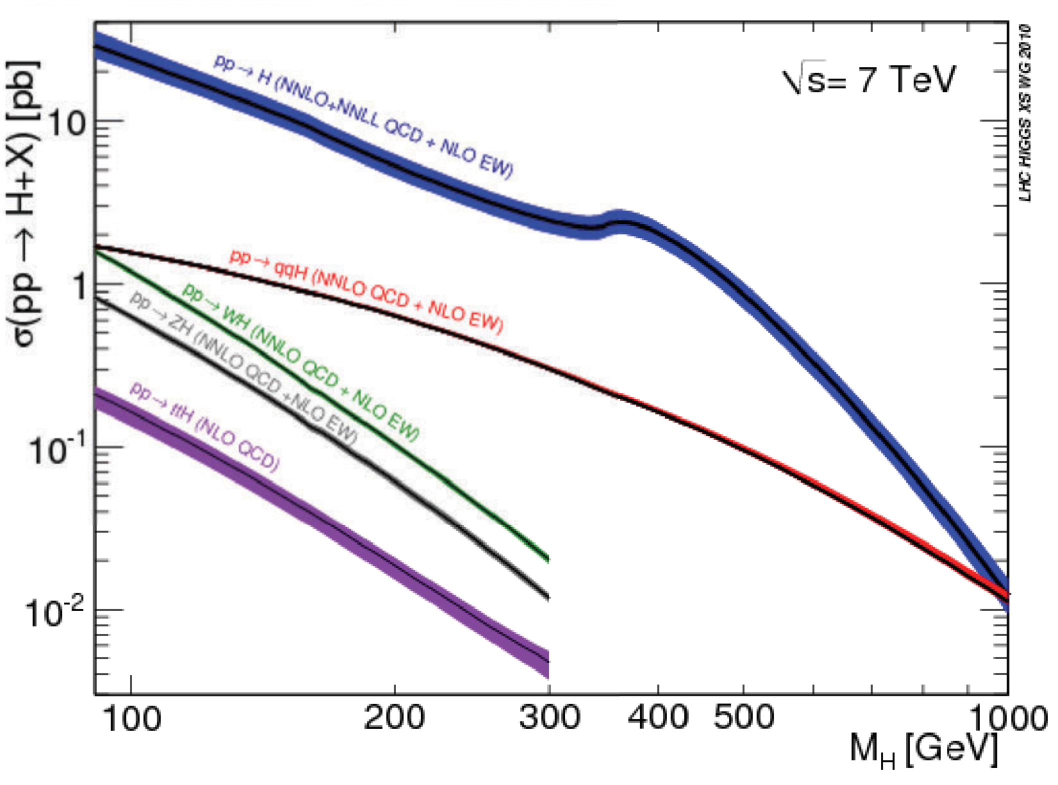
Higgs Boson Production at the LHC

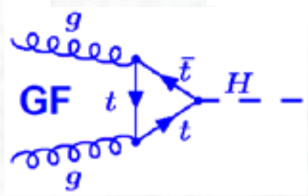


Gluon fusion (ggF)

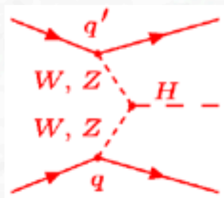
Vector boson fusion (VBF)

Higgs Boson Production at the LHC

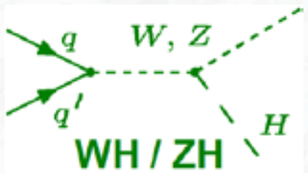




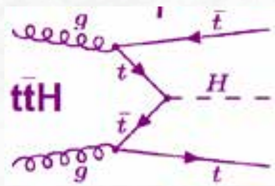
Gluon fusion



Vector boson fusion



WH/ZH associated production



tt associated production

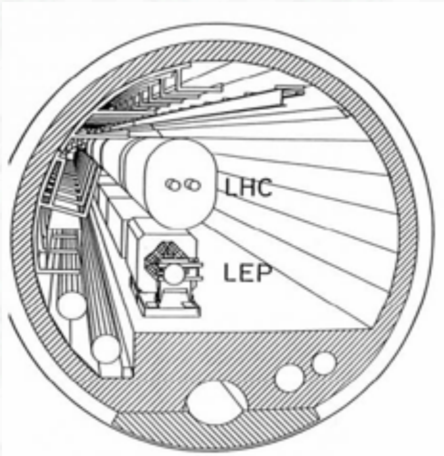
*) LHC Higgs cross-section working group;

(N)NLO calculations: Huge theory effort

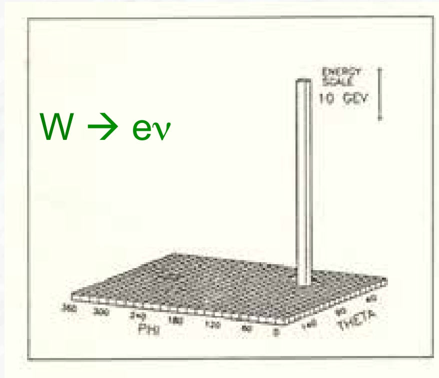
LHC for theorists: "Long and Hard Calculations"

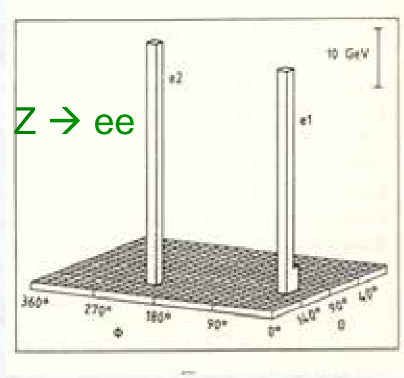
The first “experimental steps”

1984: CERN and ECFA* workshop in Lausanne,
Marks the first official recognition of the concept of the LHC



“The real belief that a ‘dirty’ hadron collider can actually do great discovery physics came from the UA1 and UA2 experiments with their W and Z boson discoveries at CERN (1983)”





1990: ECFA workshop in Aachen, Large Hadron Collider

1992: ECFA workshop in Evian: Four Expression of Interest
ASCOT, EAGLE, CMS, L3* → ATLAS + CMS

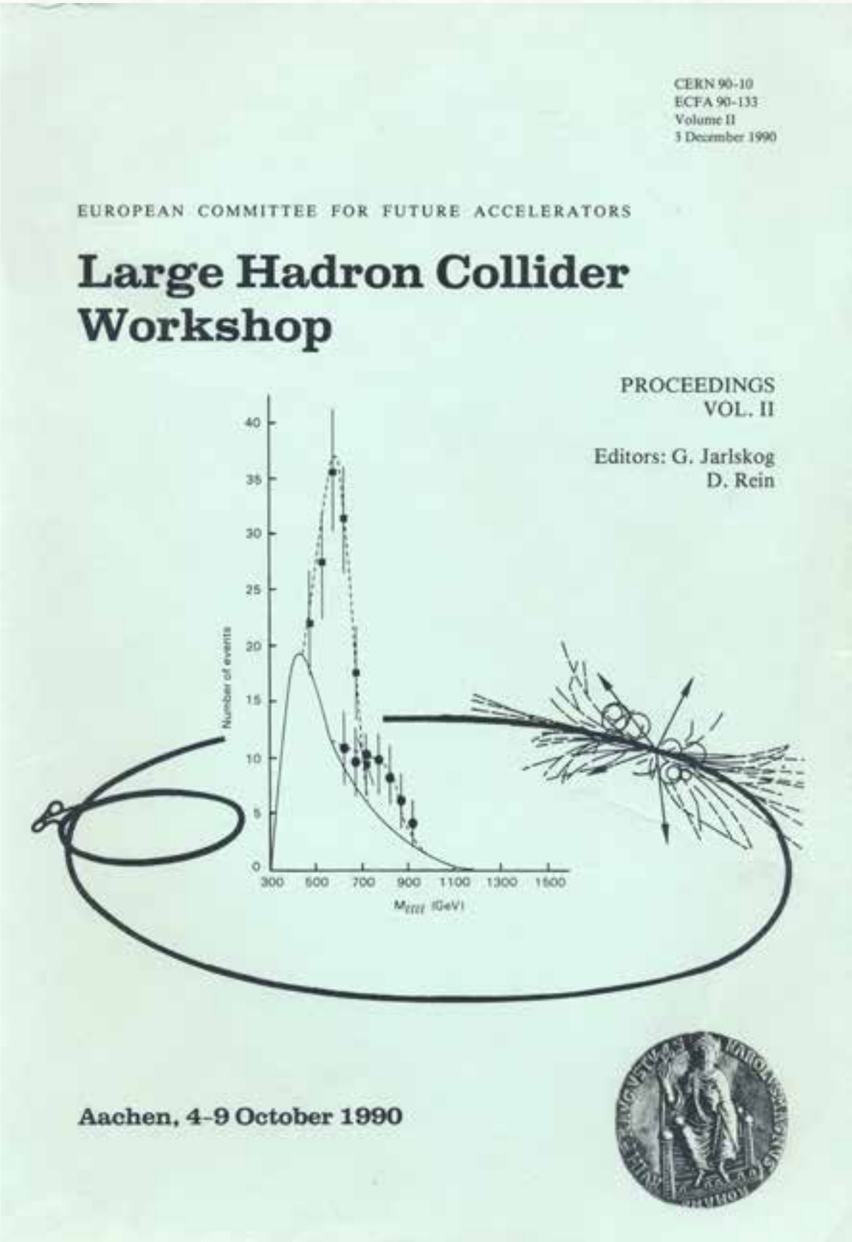
1993: Proposal of LHC with commissioning in 2002

1994: Approval of two-stage construction

1997: Approval of a single-stage 14 TeV LHC for completion in 2005

* ECFA: European Committee for Future Accelerators

The first serious studies



EXPERIMENTAL REVIEW OF THE SEARCH FOR THE HIGGS BOSON

Daniel Froidevaux

This review will limit its scope to the search for the Standard Model Higgs boson, H, at the LHC, for $\sqrt{s} = 16$ TeV. Integrated luminosities of 10^5 pb^{-1} per year of running will be used throughout, unless otherwise stated.

The search for charged Higgs bosons will be covered by the top physics working group [1], and the search for scalar or pseudoscalar neutral Higgs bosons from the Minimal Supersymmetric Standard Model has been summarised in a theoretical overview [2], since no detailed experimental simulations have yet been carried out in this context.

This review would not have been possible without the work of many people, theorists and experimentalists, who have participated in the Higgs working group studies for the Aachen workshop over a relatively short period of about 9 months. It will be divided into four main chapters :

1. $H \to ZZ, Z^*Z^* \to 4$ leptons
M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen, R. Kleiss, A. Nisati and T. Sjöstrand

2. Intermediate mass Higgs

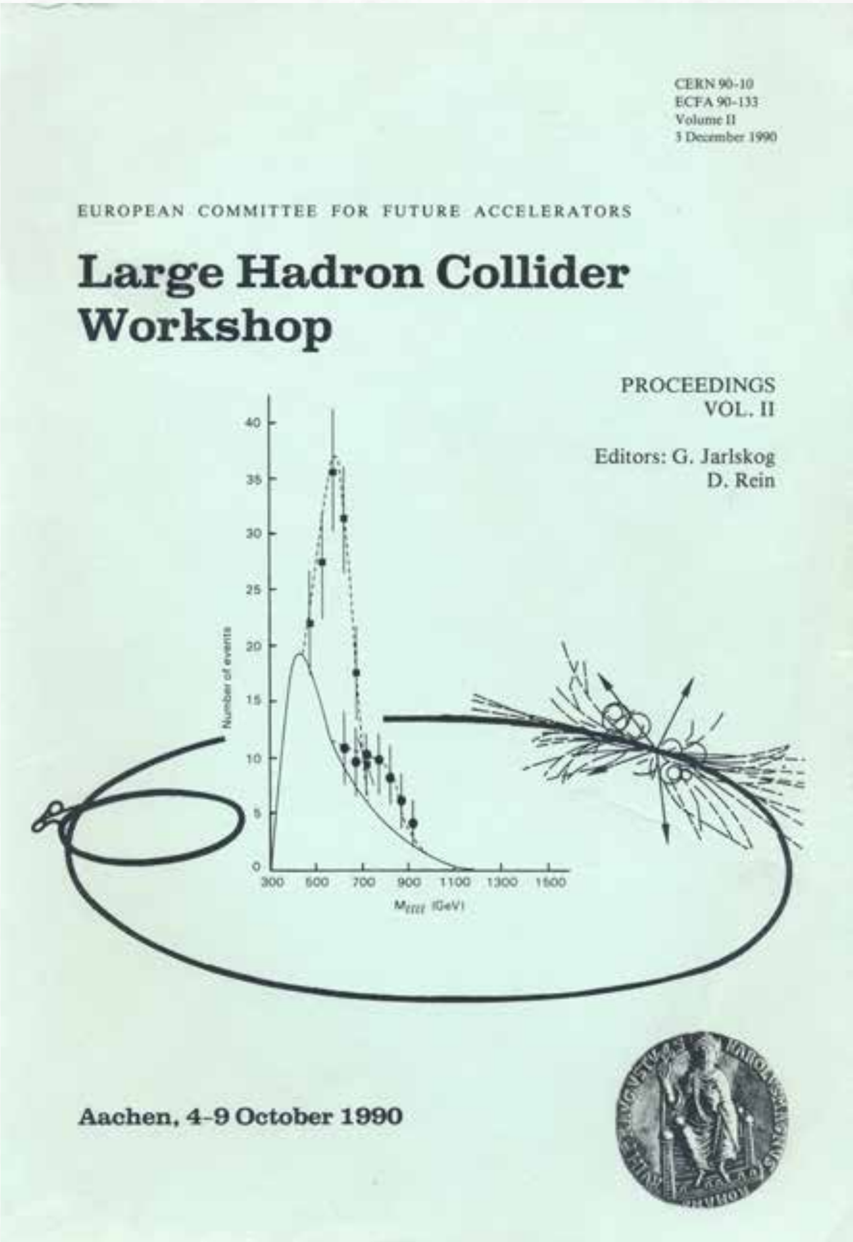
a) $H \to \gamma\gamma$, WH with $W \to \ell\nu$, $H \to \gamma\gamma$, and ZH with $Z \to \ell\ell$, $H \to \gamma\gamma$
L. DiLella, A. Djouadi, R. Kleiss, Z. Kunszt, G. Pancheri, C. Seez, W.J. Stirling and T. Virdee
This topic is reviewed in detail in the summary given by C. Seez [3]. Only the main conclusions will be discussed here.

b) $H \to \tau\tau$
F. Anselmo, K. Bos, L. DiLella and B. Van Eijk

c) WH with $W \to \ell\nu$, $H \to jj$ or $b\bar{b}$ and ZH with $Z \to \ell\ell$, $H \to jj$ or $b\bar{b}$
L. Poggioli

3. $H \to ZZ \to \ell\ell\nu\nu$, $H \to ZZ \to \ell\ell jj$, $H \to WW \to \ell\nu jj$ for m_H large
U. Baur, D. Froidevaux, E.W.N. Glover and M.H. Seymour

The first serious studies



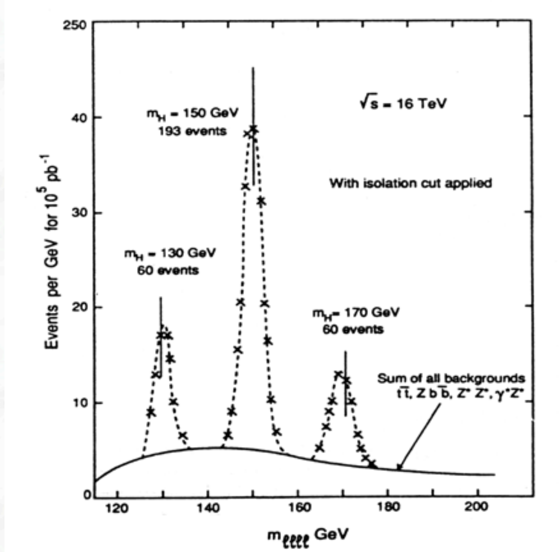


FIG. 8

II. INTERMEDIATE MASS HIGGS

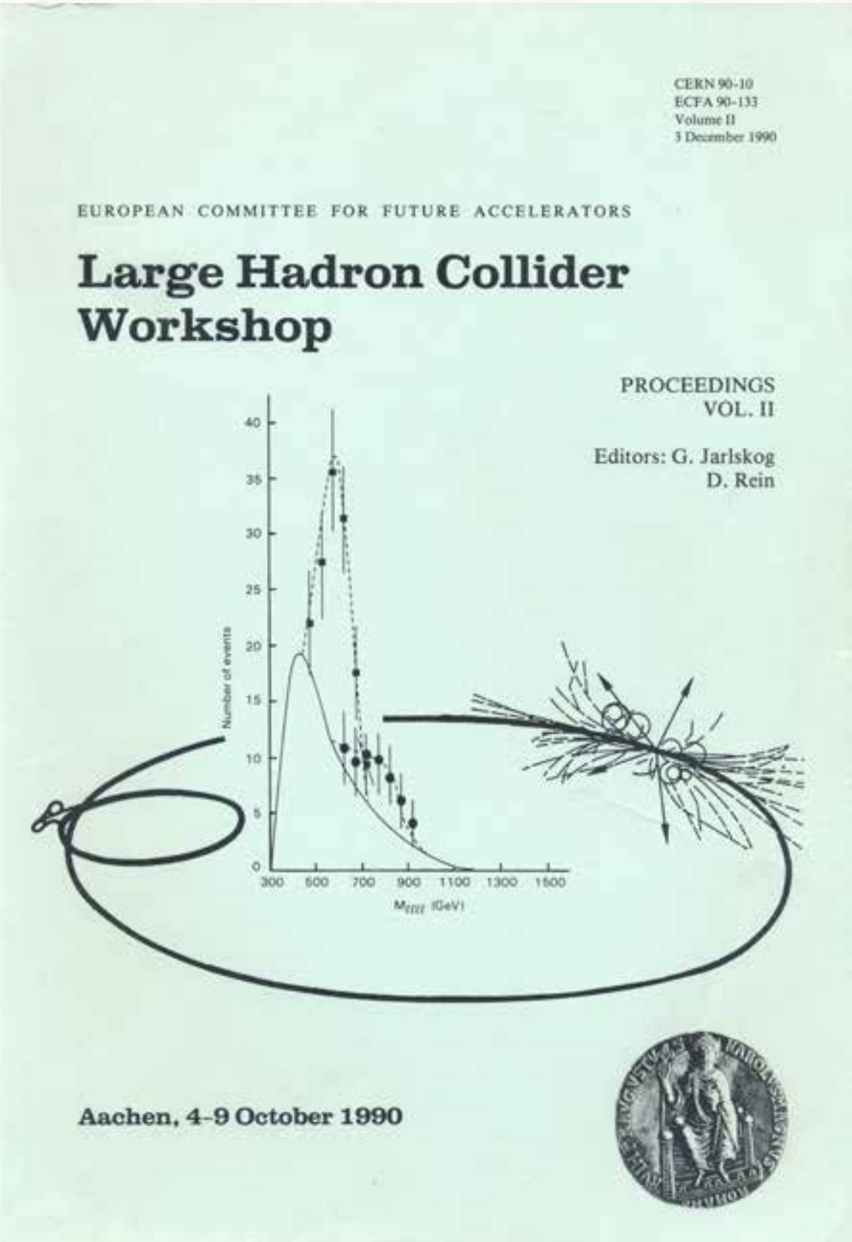
The search for the intermediate mass Higgs, $m_Z \le m_H \le 2m_Z$, has turned out to be one of the most difficult goals for experimental searches at the LHC or SSC. Many channels have been proposed and studied [16], especially in the context of SSC. In this workshop, a lot of effort was also devoted to this subject, with special focus on the problems linked with the higher luminosity at LHC.

We have seen in the previous section, that, for $130 \le m_H \le 2m_Z$, the Higgs boson can be detected in the channel $H \rightarrow Z^*Z^* \rightarrow \ell\ell\ell\ell$, provided the detector can identify low energy isolated electrons and muons. In the following we shall describe the conclusions of our working group on the other possible channels in this mass range.

(A) The "Golden decay channel":

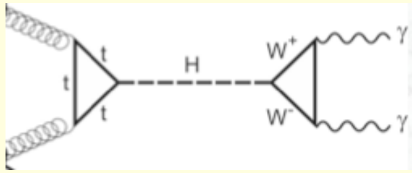
$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ \ell^+\ell^-$ (ℓ = e, μ)

The first serious studies



(B) The "Rare decay channel":

$H \rightarrow \gamma\gamma$



"None ot the other possible channel provides any hope to discover a Higgs boson in this mass range."

II. INTERMEDIATE MASS HIGGS

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II.4 Conclusions on intermediate mass Higgs, for $m_Z \leq m_H \leq 130$ GeV

With an integrated luminosity of 10^5 pb^{-1}, a signal from $H \rightarrow \gamma\gamma$ decays can be observed at LHC, for $80 \leq m_H \leq 150$ GeV, through a combination of the $H \rightarrow \gamma\gamma$ and WH, with $W \rightarrow \ell\nu$ and $H \rightarrow \gamma\gamma$, decay modes. This however imposes severe constraints on the detector design (see Ref. 3 and section IV).

None of the other possible channels, which have been studied, provides any hope to discover the Higgs in this mass range. However, as discussed in Ref. 2, $\tau\tau$ decays of SUSY Higgs bosons seem to provide a promising signature in some region of parameter space.

Further major physics steps

(i) The H → WW decay channel:

1997: M. Dittmar and H. Dreiner, H → WW → ℓℓ νν as the dominant search mode at the LHC from mH = 150 – 180 GeV, Phys. Rev. D55 (1997) 167.

1999: K. Jakobs: H → WW*→ ℓℓ νν established in the ATLAS Detector and Physics Performance TDR

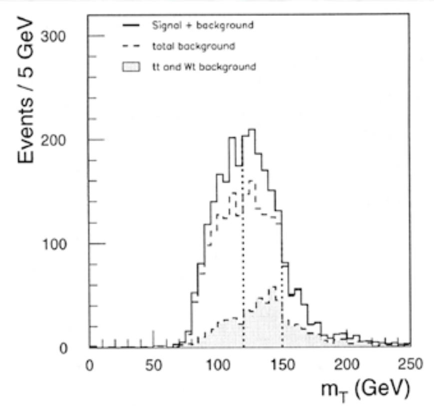
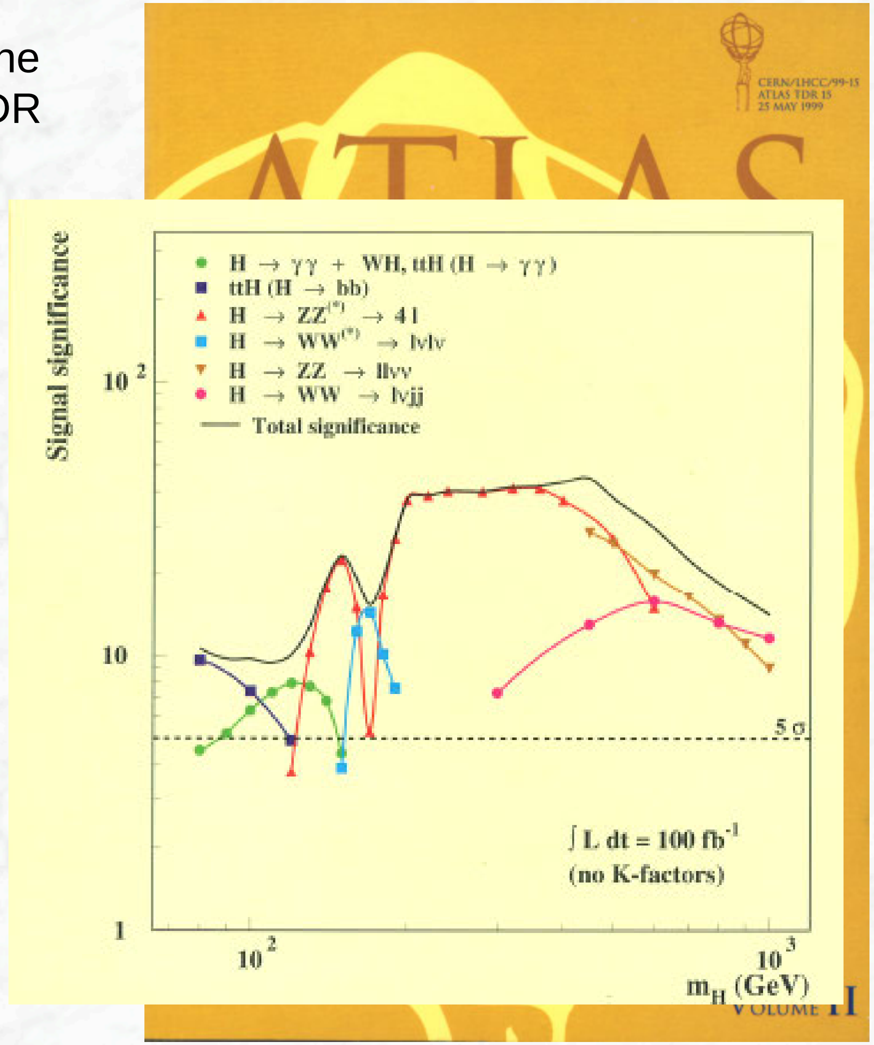


Figure 19-26 Transverse mass distribution for the summed $H \to WW^* \to l\nu l\nu$ signal (m_H = 150 GeV) and total background, for an integrated luminosity of 30 fb^{-1}. The distribution for the background alone is also shown separately. The shaded histogram represents the contributions from the Wt and $t\bar{t}$ background. The dashed lines indicate the selected signal region.



(C) The “Copious but Dirty” channel:

$H \to WW^{(*)} \to \ell^+\nu\ \ell^-\nu$ (ℓ = e, μ)

Further major physics steps

(i) The H → WW decay channel:

1997: M. Dittmar and H. Dreiner, H → WW → ℓℓ νν as the dominant search mode at the LHC from mH = 150 – 180 GeV, Phys. Rev. D55 (1997) 167.

1999: K. Jakobs: H → WW*→ ℓℓ νν established in the ATLAS Detector and Physics Performance TDR

Fermions !

(D) The “Challenge”:

qq H → qq ττ

(ii) The vector boson fusion channels:

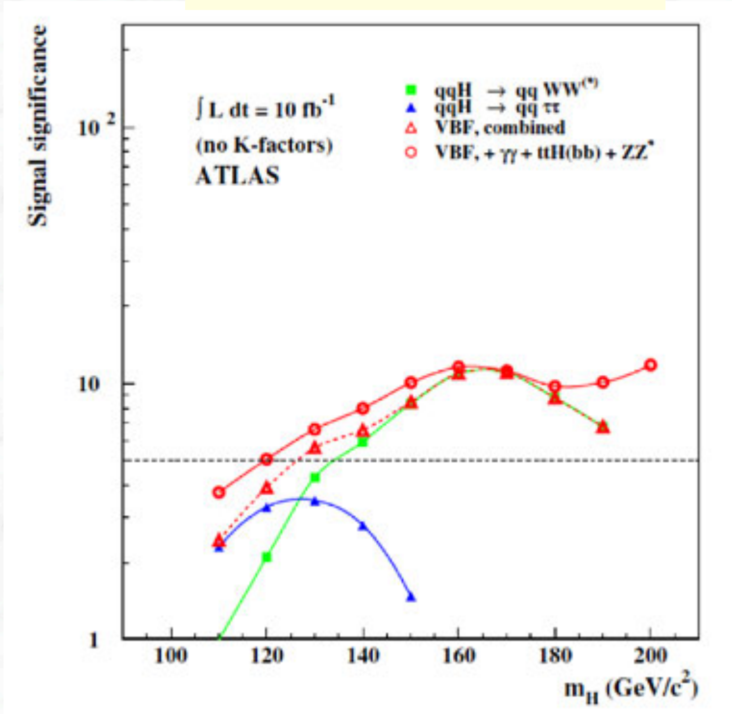
1999: D. Rainwater, D. Zeppenfeld
Vector boson fusion production at low mass,
qqH → qq WW, qqH → qqττ
2003: ATLAS Vector boson fusion paper, EPJ-C

Eur Phys J C 32, s02, s19–s54 (2003)
DOI: 10.1140/epjcd/s2003-01-010-8

EPJ C direct
electronic only

Prospects for the search for a standard model Higgs boson in ATLAS using vector boson fusion

S. Asai[8], G. Azuelos[5], C. Buttar[7], V. Cavasinni[6], D. Costanzo[6,*], K. Cranmer[9], R. Harper[7], K. Jakobs[4], J. Kanzaki[3], M. Klute[1], R. Mazini[5], B. Mellado[9], W. Quayle[9], E. Richter-Was[2], T. Takemoto[3], I. Vivarelli[6], Sau Lan Wu[9]



ATLAS Overview Week Freiburg 2004

ATLAS Overview Week Freiburg 2004

Further major physics steps

(iii) Higgs boson couplings:

2003: T. Plehn, D. Rainwater and D. Zeppenfeld,
Determining the structure of the Higgs couplings at the LHC
Phys. Rev. Lett. 88 (2003) 051801.

2003: M. Dührssen, *"Studie zur Bestimmung der Higgs-Boson-Kopplungs-parameter im ATLAS-Experiments am LHC",*
Diplomarbeit, Universität Mainz
2004: M. Dührssen et al., Extracting Higgs boson couplings from CERN LHC data", Phys. Rev. D70 (2004) 113009.

(iv) H → bb revival

2008: J. Butterworth et al., *Jet substructure as a new Higgs search tool at the LHC*, Phys. Rev. Lett. 100 (2008) 242001.
2009: G. Piacquadio, C. Weiser et al. ATLAS sensitivity to the Standard Model Higgs boson in the WH and ZH channels at high transverse momenta, ATL-PHYS-PUB-2009-088.

(E) The "Hope(less)":

WH → $\ell\nu$ bb
ZH → $\ell\ell$ bb

Another try for Fermions!

Little Higgs models

Composite Higgs bosons

MSSM Higgs bosons

Dark Higgs

More Higgs bosons

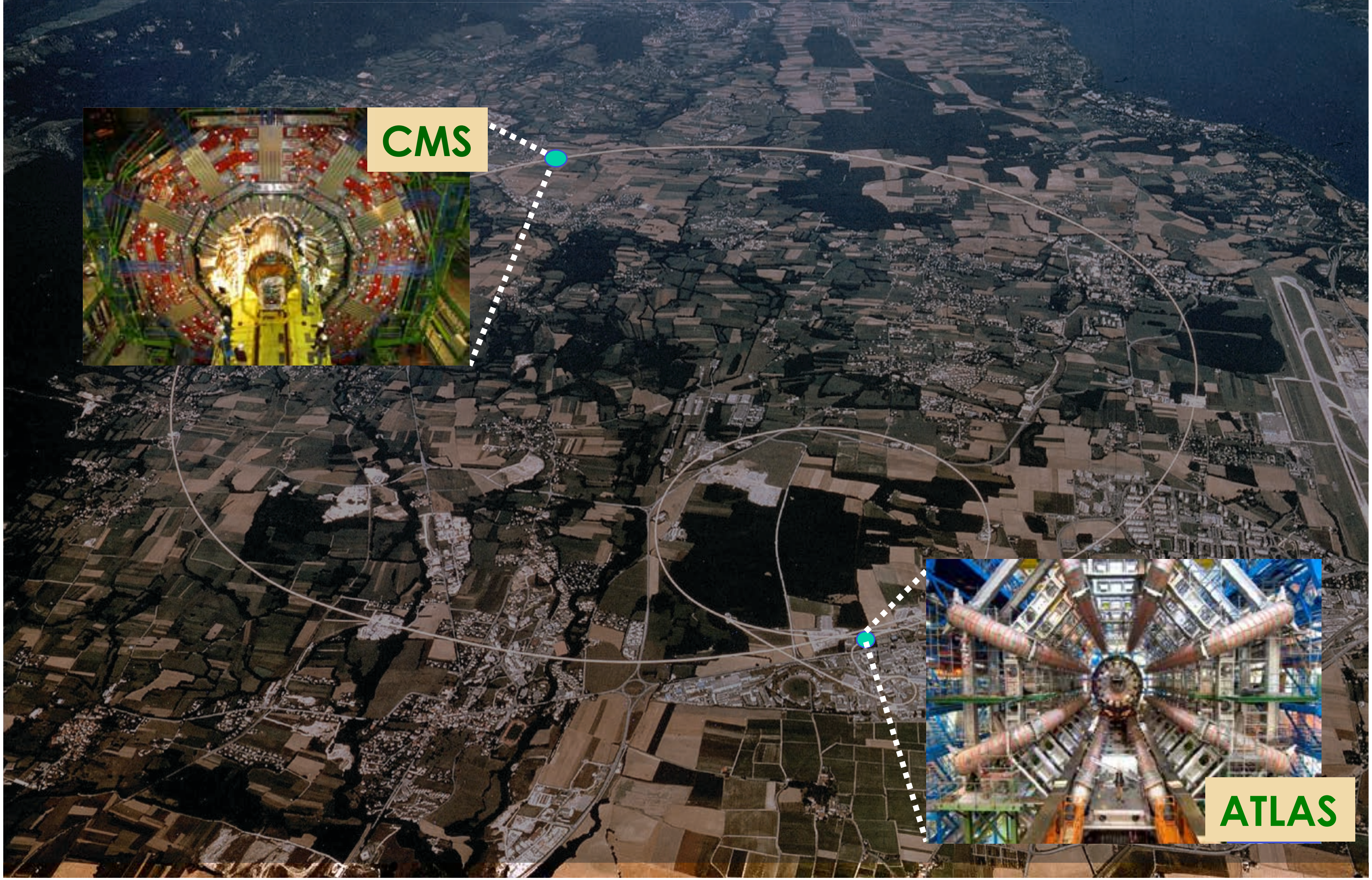
SUSY Higgs

Ausgeschmierte Higgs

Heidi Higgs

No Higgs at the LHC

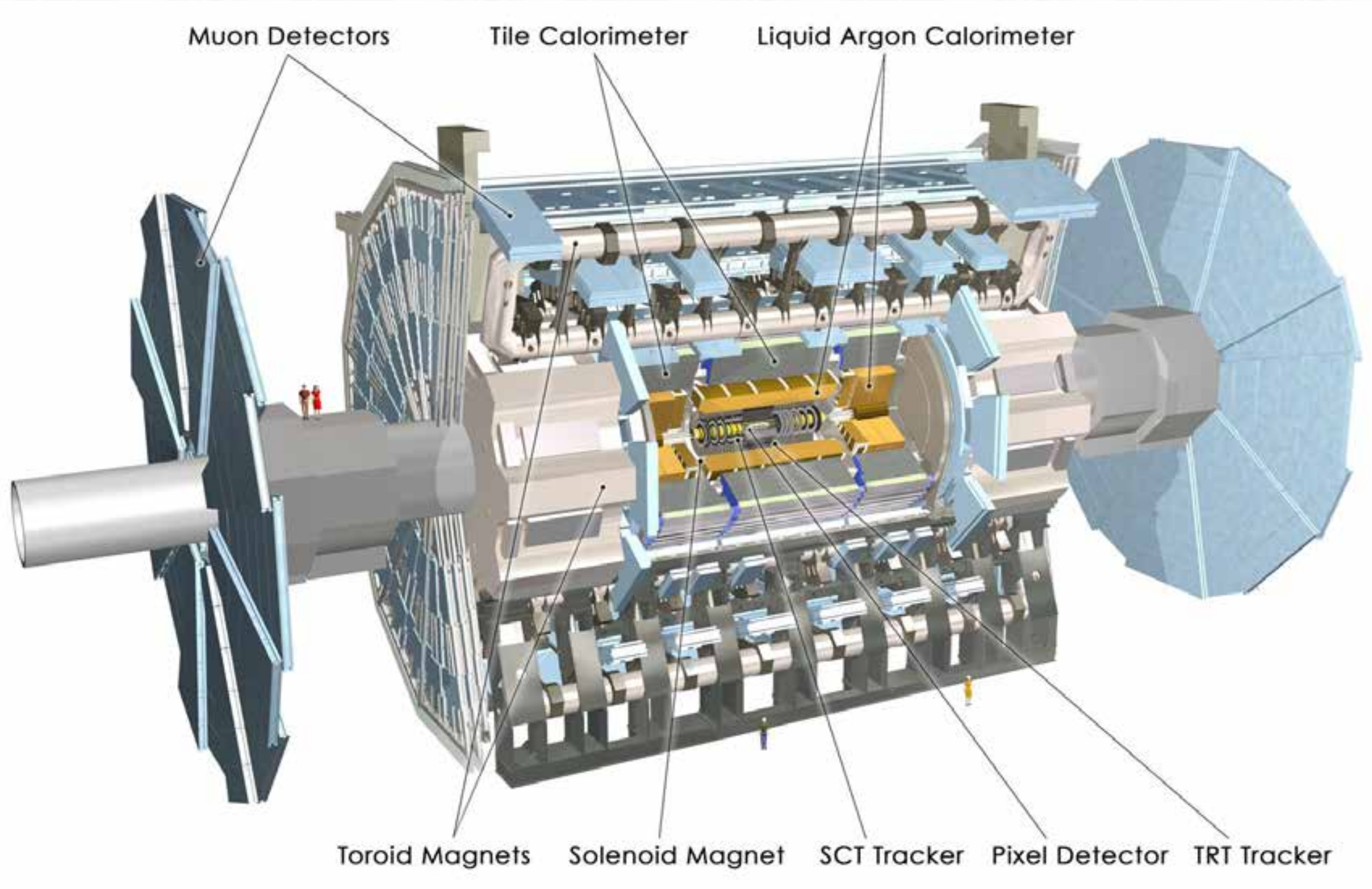
The Large Hadron Collider



Ein Blick in den Beschleunigertunnel des LHC

Inbetriebnahme 2008 / 2009
nach ~15 Jahren Entwicklungs- und Bauzeit

The ATLAS experiment



Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons