Higgs boson search and discovery

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HASCO Summer School
– Goettingen, July 2016 –

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

ATLAS

Introduction

What will we discuss today?

➔ have only 2 hours for this topic

➔ cannot cover all the analyses and plans in that time

➔ Will focus on:

$\hookrightarrow$ Basics of electroweak symmetry breaking

$\hookrightarrow$ How was the Higgs boson predicted (and why the name)?

$\hookrightarrow$ How did we gather intel over the years and how was it found?

$\hookrightarrow$ What do we know now? Is this already the end of the story or can we learn more?

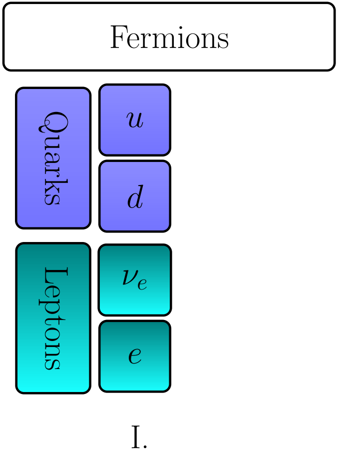
Disclaimer

Will show results from ATLAS, CMS, D0, CDF and LEP experiments

➔ due to limited time: cannot always show all of the results,
a slight bias for ATLAS to be expected!

$\Rightarrow$ **Don't take it personally ;)**

The Standard Model of Particle Physics



Fermions

Quarks

u

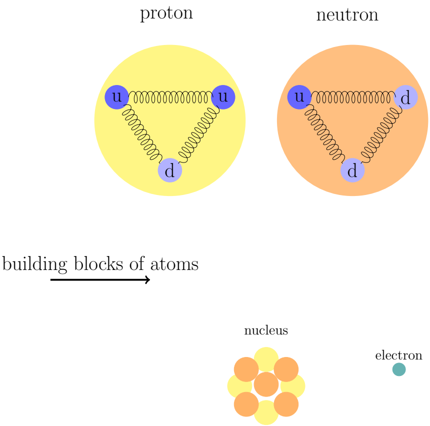
d

Leptons

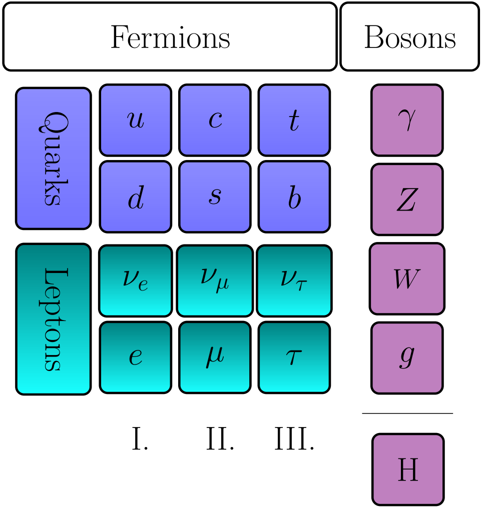
ν_e

e

I.



The Standard Model of Particle Physics: Gauge Bosons



Fermions				Bosons
Quarks	u	c	t	γ
	d	s	b	Z
Leptons	ν_e	ν_μ	ν_τ	W
	e	μ	τ	g
	I.	II.	III.	H

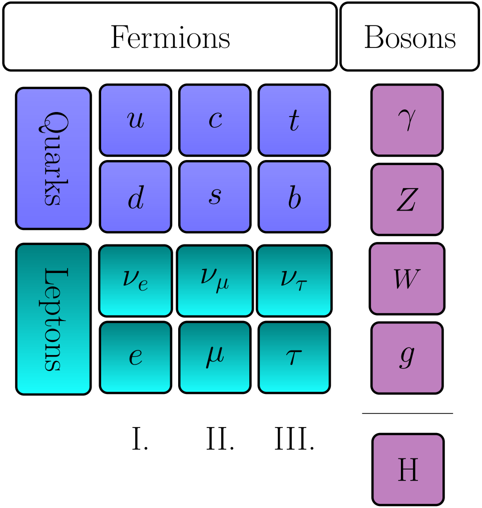
➔ electromagnetic interaction

➔ neutral weak interaction

➔ charged weak interaction

➔ strong interaction

The Standard Model of Particle Physics: Gauge Bosons



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➔ electromagnetic interaction

➔ neutral weak interaction

➔ charged weak interaction

➔ strong interaction

➔ 4th July 2012: Observation of *Higgs-like* Boson at the LHC!

Why is the Higgs-boson special in the SM?

➔ neither quark nor lepton, which are building blocks of other matter

➔ also not a gauge boson, so it does not carry any force

➔ only scalar in the SM

➔ mechanism postulated long before many SM particles were known!

xkcd.com

What was known in particle physics?

➔ 1897: electron by J.J. Thomson

➔ 1905: the photon in the photo-electric effect

➔ 1927: first idea of anti-matter (Dirac-sea)

➔ 1930: first idea of neutrinos (Pauli)

➔ 1937/47: muon in cloud chamber, pions in photo-emulsions

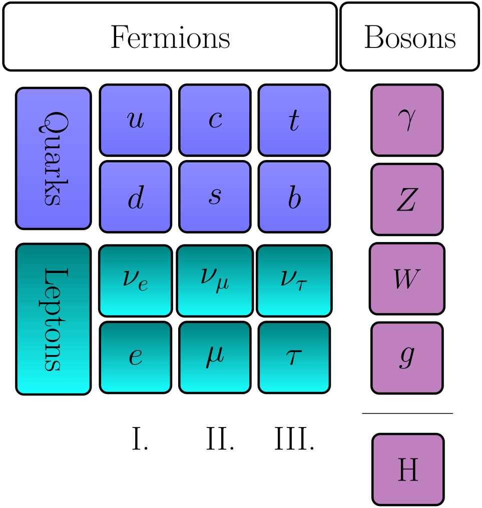
➔ 1947: kaons (Rochester and Butler)

➔ 1964: first mentioning of quarks (Gell-Mann, Zweig)

↪ three quarks postulated: up, down and strange

↪ first more a math trick: introduce colour as new quantum number

So from our nice list of elementary particles here...



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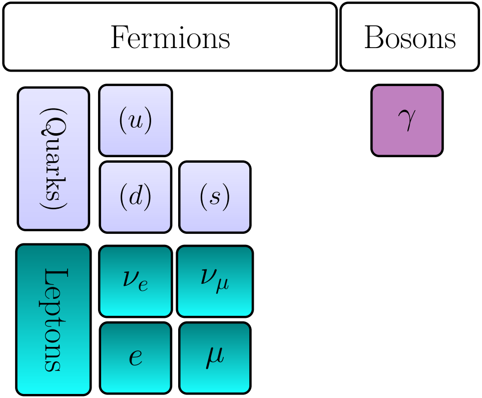
	I.	II.	III.	H

... only these were known (postulated) in 1964



Fermions

Bosons

(Quarks)

(u)

(d) (s)

Leptons

ν_e ν_μ

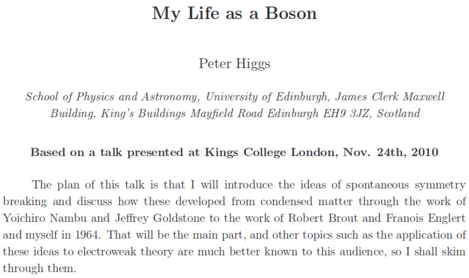
e μ

γ

➔ quarks not discovered yet, only postulated

➔ add. particles known: proton, neutron, kaons, pions

Historical context



My Life as a Boson

Peter Higgs

School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, King's Buildings Mayfield Road Edinburgh EH9 3JZ, Scotland

Based on a talk presented at Kings College London, Nov. 24th, 2010

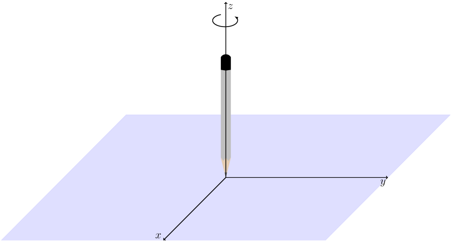
The plan of this talk is that I will introduce the ideas of spontaneous symmetry breaking and discuss how these developed from condensed matter through the work of Yoichiro Nambu and Jeffrey Goldstone to the work of Robert Brout and Franois Englert and myself in 1964. That will be the main part, and other topics such as the application of these ideas to electroweak theory are much better known to this audience, so I shall skim through them.

➔ nice summary of the history of spontaneous symmetry breaking from Peter Higgs ▸ Link to full transcript

➔ lets go through a few cornerstones of the development

What is Spontaneous Symmetry Breaking (SSB)?

Simple graphic example:

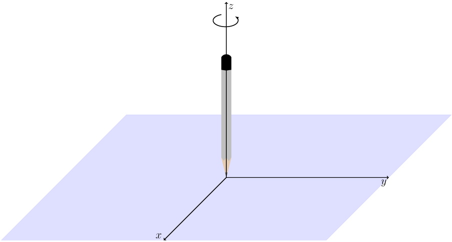


Pencil stands on its top, rotationally symmetric around z-axis.

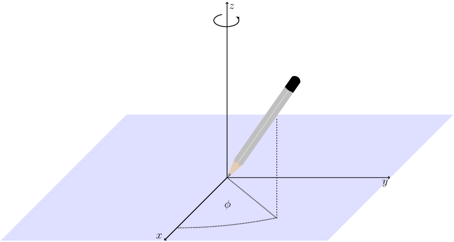
➔ left: state is rotationally invariant, but highly unstable

What is Spontaneous Symmetry Breaking (SSB)?

Simple graphic example:



Pencil stands on its top, rotationally symmetric around z-axis.

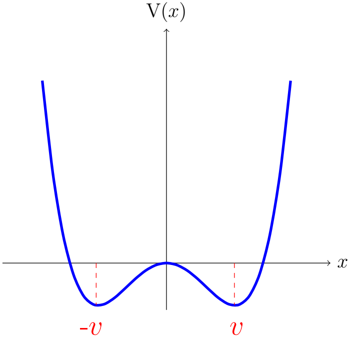


Pencil drops to one side (goes into ground state)
$\Rightarrow$ symmetry is spontaneously broken

➔ left: state is rotationally invariant, but highly unstable

➔ right: system goes into stable ground state, but symmetry is broken

The “Mexican-hat” potential



- ➔ potential is rotationally invariant, V(0) is unstable
- ➔ ground-state has non-vanishing vacuum expectation value *v*
- ➔ where does this play a role in physics?

Higgs-mechanism in a nutshell

Space is filled with Higgs field

Room is filled with physicists

Particle interacts with field

Einstein enters the room

Interaction with field gives mass to particle

People cluster around Einstein and slow him down.

Where does the Higgs particle come in then?

Excitation of Higgs field.

Rumour spread: Einstein is coming!

Higgs boson created by self-interaction of field.

People cluster in groups to talk about rumour.

The beginnings of spontaneous symmetry breaking (SSB)

1928: Werner Heisenberg

➔ first idea stems from condensed matter physics

➔ Heisenberg: theory of ferromagnetism

1947: Nicolay Bogoliubov

➔ Superfluidity (bose condensate)

➔ phase transformation (U(1) symmetry)

1950: Ginzburg & Landau

➔ need charged bose condensate for superconductivity

➔ full theory in 1957 by Bardeen, Cooper, Schrieffer (BCS-Theory)

Further developments for SSB

1960/61: Nambu

➔ with Jona-Lasinio: “Dynamical Model of Elementary Particles based on and Analogy with Superconductivity” ▸ Phys.Rev. 124 246

➔ at that time: no quarks known yet

➔ introduced chiral symmetry SU(2) x SU(2) which acts on massless fermion fields

➔ ground state is spont. broken, so fermions are massive (fermions here are protons and neutrons!)

Effect of super-conductivity

- below a certain critical temperature $T_{\text{crit.}}$ (a few Kelvin) :

  ↪ resistance in some elements (W, Hg,v...) almost vanishes
- static magnetic field is forced outside the super-conductor:

  ↪ Meissner-Ochsenfeld effect
- described in BCS-theory 1957 (multi-particle theory)
- was awarded the nobel prize in 1972

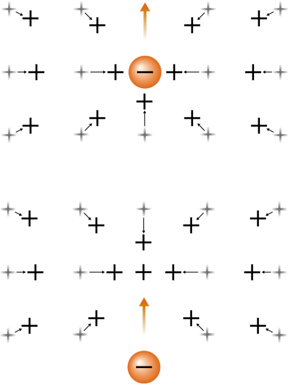
➔ Lance Dixon: ▸ Link full text
From superconductors to supercolliders

Super-conductivity: Cooper-pairs

➔ at very low temperatures: atomic movement quite low

➔ sketch: electron attracts atom, lattice get polarised

➔ second electron gets attracted from positive charge



Two electrons form pair: Cooper-pair

$\hookrightarrow$ two electrons cannot be in the same state (Pauli-principle)

$\hookrightarrow$ Cooper-pairs have net spin of 0: $\Rightarrow$ boson!

$\hookrightarrow$ can go into ground state simultaneously (condensate)

$\hookrightarrow$ Cooper pairs have charge of 2e, Higgs boson has weak charge

The Nambu-Goldstone boson

The Goldstone theorem

“If you have a symmetry which is spontaneously broken, massless scalar particles appear, so-called Nambu-Goldstone bosons.”

1960: Goldstone

➔ paper on field theories, includes elementary scalar fields and the “Mexican hat” potential

➔ 1962: prove of Goldstone theorem with Weinberg and Salam

Why are Goldstone bosons a problem?

1. if the particle is massless, it should have been easy to find it
2. if it exists, then stars would also radiate Goldstone bosons instead of photons

⇒ Goal now: Try to get rid of massless Goldstone bosons!

Spontaneous symmetry breaking [1]

Start from classical Lagrangian:

$$\mathcal{L} = T - V = E_{\mathrm{kin}} - E_{\mathrm{pot}}$$

with ϕ being a complex scalar field:

$$\mathcal{L} = (\partial_\mu \phi)(\partial^\mu \phi^*) - \mu^2 \phi\phi^* - \lambda(\phi\phi^*)^2$$

with $\mu^2 \rightarrow$ mass of field quanta and $\lambda \rightarrow$ self interaction.

Look at group U(1) of global transformations:

$$\phi(x) \rightarrow \phi'(x) = e^{-i\theta}\phi(x)$$

For $\phi = \mathrm{const.} \Rightarrow T = 0$

---

[1] Based on: *An introduction to gauge theories and modern particle physics* by Elliot Leader & Enrico Predazzi

$$V = \mu^2\phi\phi^* + \lambda(\phi\phi^*)^2 \quad \text{with} \quad \rho = \phi\phi^*$$

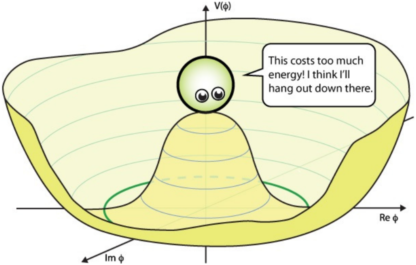
$$V(\rho) = \mu^2\rho + \lambda\rho^2$$

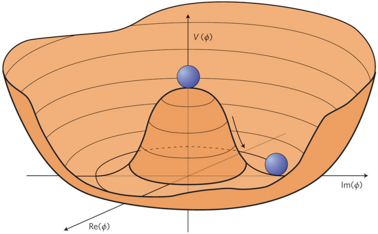
choose $\lambda > 0$. For $\mu^2 > 0$: one minimum at $\rho = 0$.

$$\text{For} \quad \mu^2 < 0 \Rightarrow \rho_{\text{min}} = \frac{-\mu^2}{2\lambda}$$

$\Rightarrow$ ground state is ring around zero with radius $\sqrt{\frac{-\mu^2}{2\lambda}}$.

➔ $\phi = 0$ is unstable!





All points on ring are equal, can choose point on real axis:

$$\phi(x) = \frac{1}{\sqrt{2}}[v + \xi(x) + i\chi(x)]$$

$$\text{with} \quad \xi = \chi = 0 \quad \text{in ground state.}$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \chi)^2 - \lambda v^2 \xi^2 - \lambda v \xi(\xi^2 + \chi^2) - \frac{1}{4}\lambda(\xi^2 + \chi^2)^2 + const.$$

➔ $m_\xi^2 = 2\lambda v^2$ generated spontaneously, no mass term for χ field.

The BEH mechanism

Start as before with $\mathcal{L} = T - V$ but this time require invariance under **local** U(1) transformation.

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ieA_\mu$$

and add kinetic term $-1/4 F_{\mu\nu}F^{\mu\nu}$.

$$\Rightarrow \mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + [(\partial_\mu - ieA_\mu)\phi^*][(\partial_\mu + ieA_\mu)\phi] - \mu^2\phi\phi^* - \lambda(\phi\phi^*)^2$$

Local gauge transformation:

$$U(\theta) = e^{-i\theta(x)}$$

The BEH mechanism II

Lagrangian is invariant under local gauge trafo $U(\theta)$ with:

$$\phi(x) \;\rightarrow \phi'(x) \;= e^{-i\theta(x)}\phi(x)$$

$$\phi^*(x) \rightarrow \phi^{*'}(x) = e^{i\theta(x)}\phi^*(x)$$

$$A_\mu(x) \rightarrow A^{'}_\mu(x) = A_\mu(x) + \tfrac{1}{e}\partial_\mu\theta(x)$$

and choose again $\lambda > 0$. For $\mu^2 < 0$ as before.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \underbrace{\frac{e^2v^2}{2}A_\mu A^\mu}_{\text{mass for gauge field}} + \frac{1}{2}(\partial_\mu\xi)^2 + \underbrace{\frac{1}{2}(\partial_\mu\chi)^2}_{\text{massless scalar}} - \underbrace{\frac{1}{2}(2\lambda v^2)\xi^2}_{\text{massive scalar}} - \underbrace{evA_\mu\partial^\mu\chi}_{\text{unphysical!}} + \ldots$$

Now have to solve two problems

① have unphysical term as shown on previous slide

② have too many degrees of freedom!

Solution: choose a different gauge $\phi = (v + h(x))e^{i\frac{\theta(x)}{v}}$

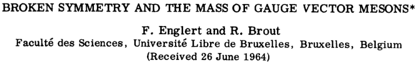
With transformations: $\phi \to e^{-i\frac{\theta(x)}{v}}\phi$ and $A_\mu \to A_\mu + \frac{1}{ev}\partial_\mu\theta$.

Then the Lagrangian looks as follows:

$$\underbrace{\frac{1}{2}\partial_\nu h\partial^\nu h - \lambda\nu^2h^2 - \lambda\nu h^3 - \frac{1}{4}\lambda h^4}_{\text{massive scalar}} + \underbrace{\frac{1}{2}e^2\nu^2A_\mu A^\mu - F^{\mu\nu}F_{\mu\nu}}_{\text{massive gauge boson}} + \underbrace{\frac{1}{2}e^2A_\mu A^\mu h^2 + \nu e^2A_\mu A^\mu h}_{\text{interaction with gauge boson}}$$

⇒ The Goldstone boson is absorbed, the unphysical term vanished and the d.o.f. are correct.

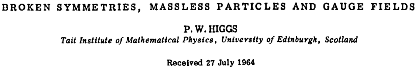
Spontaneous symmetry breaking papers



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)

▸ Phys.Rev.Lett. 13 321

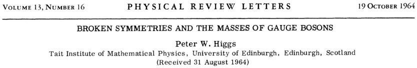


BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

▸ Phys.Rev.Lett. 12 2

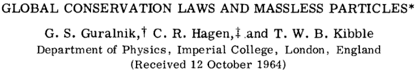


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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)

▸ Phys.Rev.Lett. 13 508



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)

▸ Phys.Rev.Lett. 13 585

What is the difference between the three approaches?

Higgs:

- started from classical Lagrangian
- prediction of massive scalar boson

Brout/Englert:

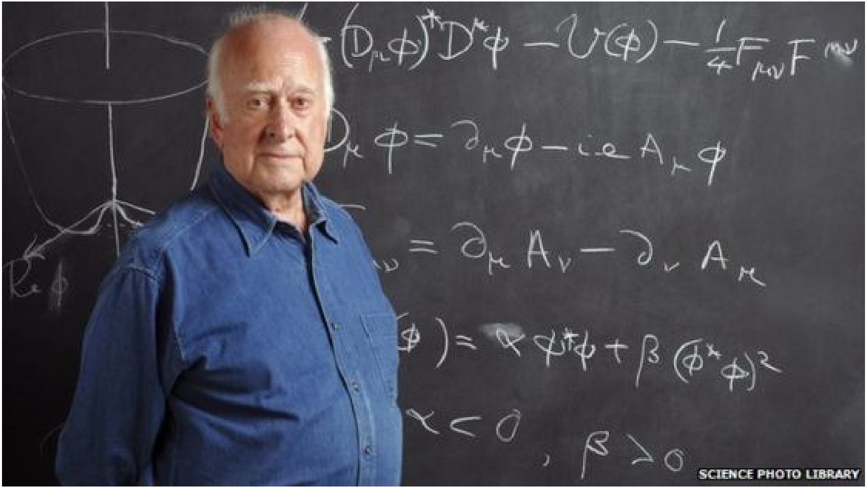
- solution on quantum level: starting from Feynman diagrams
- scalar boson implied, but not explicitly mentioned

Hagen, Kibble, Guralnik:

- remove problem of massless Goldstone bosons
- more detailed, discussed more technical aspects

⇒ Back then, a lot of people believed the papers were wrong...

And the Higgs boson?

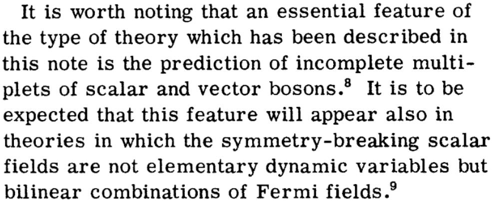


When approaches are equivalent, why “Higgs”-boson?

➔ one reason: people got order wrong and cited Higgs paper first

➔ then: first version of Higgs paper got rejected

↪ when revising the paper for resubmission, Higgs added the following:



It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

➔ first explicit mentioning of the scalar boson

➔ nowadays: Brout-Englert-Higgs (BEH) Boson!

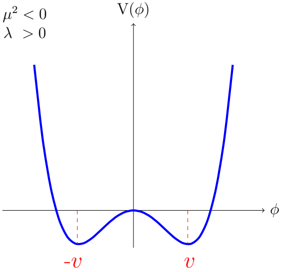
The BEH mechanism in simpler form

Introduce a doublet of complex, scalar fields ϕ:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad .$$

The corresponding Higgs potential is of the form:

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



$\Rightarrow$ get a non-vanishing vacuum-expectation value $v = \sqrt{-\mu^2/\lambda}$

Breakdown of full Lagrangian for $\mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$

With the derivative:

$$D^\mu = \partial^\mu + ig\frac{\vec{\tau}}{2}\vec{W}^\mu + ig'\frac{Y}{2}B^\mu \quad ,$$

we can express the Lagrangian as:

$$\mathcal{L}_{\mathrm{SU(2)_L}\times\mathrm{U(1)_Y}} = \underbrace{-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{\mathcal{L}_{\mathrm{Gauge}}} + \underbrace{\bar{\psi}_L\gamma^\mu(iD^\mu)\psi_L + \bar{\psi}_R\gamma^\mu(i\partial_\mu - g'\frac{Y}{2}B_\mu)\psi_R}_{\psi_{\mathcal{L}}\,\mathrm{Fermions}}$$

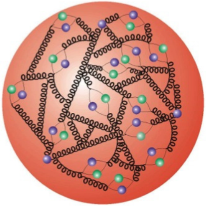
$$+ \underbrace{|(iD^\mu)\phi|^2 - V(\phi)}_{\mathcal{L}_{\mathrm{Higgs}}} - \underbrace{(\lambda_l\bar{\psi}_L\phi\psi_R + \lambda_q\bar{\psi}_L\phi\psi_R + h.c.)}_{\mathcal{L}_{\mathrm{Yukawa}}}$$

Mistake often made:

➔ The Higgs boson is NOT the origin of mass!

↪ it allows for massive elementary particles in the theory

Example proton:



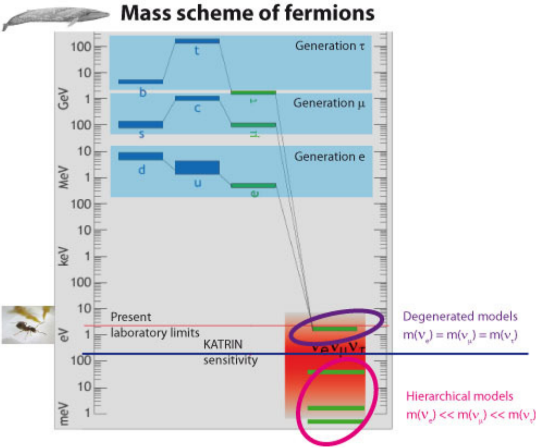
➔ mass proton: 938 MeV

➔ $2 \cdot m_{\mathrm{u-quark}} + m_{\mathrm{u-quark}} + m_g \approx 11.5$ MeV

⇒ missing a factor of ≈ 82 !

⇒ proton mass comes mainly from QCD confinement

Three fermion generations: three mass ranges



▸ Link to sketch

➔ Does not explain the flavour hierachy seen

What happened after papers were published?

1965 Higgs:

➔ Full review paper published ▸ Phys.Rev 145 1156

➔ Ideas were shown by all authors in seminars

➔ Many people thought the idea was wrong, since the Goldstone theorem had been fully proven.

1967: Glashow, Weinberg, Salam

➔ applied SSB to electroweak theory

1970/1: Veltman and t' Hooft

➔ proof that Yang-Mills theories with masses from SSB in scalar fields are renormalizable

Electroweak theory

- introduced by Glashow, Weinberg and Salam (GWS)
- gauge group is the $\mathrm{SU(2)_L \times U(1)_Y}$
- SU(2): non-abelian SU(2), U(1) abelian U(1)
- four generators: lead to four massless fields:
  - $\hookrightarrow$ $W_1^\mu, W_2^\mu, W_3^\mu$ generated by the weak isospin
  - $\hookrightarrow$ B_μ^0 generated by the hypercharge Y

Physical particles are mixtures of these massless bosons:

$$\begin{pmatrix} Z^0 \\ \gamma \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W_3^\mu \end{pmatrix}$$

How do we get the gauge boson masses?

Remember Higgs potential as before, with $\mu^2 < 0$ and $\lambda > 0$.

$\Rightarrow$ non-vanishing vev v with $v = \sqrt{-\mu^2/\lambda}$

➔ Higgs boson mass: $m_H = \sqrt{2}\mu$.

Mass of $W^\pm$- and Z-bosons:

$$m_Z = \frac{1}{2} v g \quad \text{and} \quad m_W = \frac{1}{2} v \sqrt{g^2 + g'^2} \quad .$$

Fermion masses: from coupling of particles to Higgs field:

$\hookrightarrow$ *Yukawa* couplings λ_f:

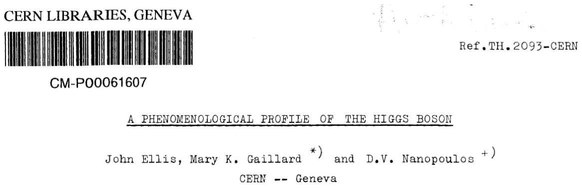
$$m_f = \frac{1}{\sqrt{2}} \lambda_f v \quad .$$

$\Rightarrow$ mass of Higgs boson would determine all couplings!

1975/76: The hunt begins...

Paper on Higgs profile:

▸ Link Paper



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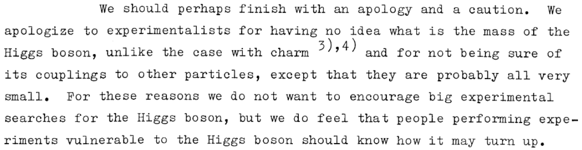
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

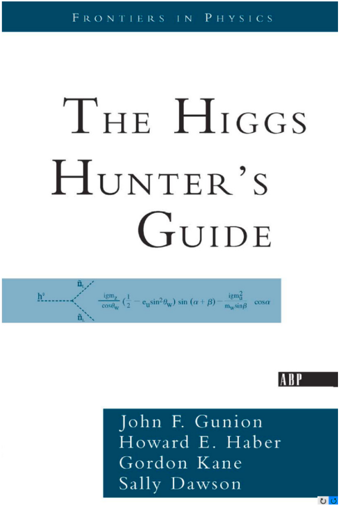
John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

Summary:



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.

The hunt begins...



FRONTIERS IN PHYSICS

THE HIGGS HUNTER'S GUIDE

ABP

John F. Gunion
Howard E. Haber
Gordon Kane
Sally Dawson

- **mass: free parameter, no prediction**
- **spin/parity: $J^{CP} = 0^{++}$**
- **couplings, production/decay modes:**
  $\hookrightarrow$ depend on m_H!

The LEP accelerator

➔ colliding electrons and positrons

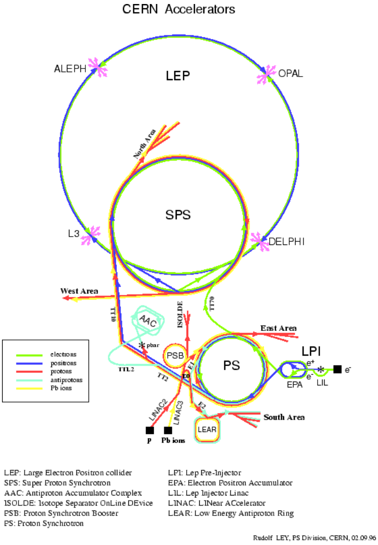
➔ from 1989 – 1995: $\sqrt{s} = 91$ GeV

➔ after 1995 upgrade to 189 GeV

➔ max. energy reached: 206 GeV

➔ decommisioned in 2000

➔ tunnel was re-used for the LHC



LEP: Large Electron Positron collider
SPS: Super Proton Synchrotron
AAC: Antiproton Accumulator Complex
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LPI: Lep Pre-Injector
EPA: Electron Positron Accumulator
LIL: Lep Injector Linac
LINAC: LINear ACcelerator
LEAR: Low Energy Antiproton Ring

Rudolf LEY, PS Division, CERN, 02.09.96

Indirect searches @ LEP and SLAC

- assume: search for new particle at accelerators

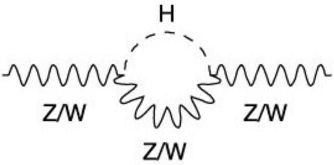
  $\hookrightarrow$ too heavy to be directly produced and observed

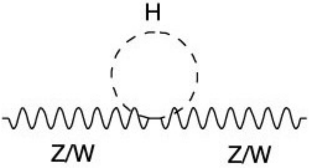
- but: if particle appears in higher-order loop corrections

  $\hookrightarrow$ will alter the actual measured quantities

- effect quite small here (< 1 %)

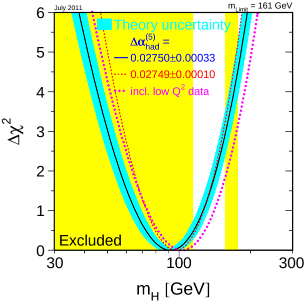
  $\hookrightarrow$ but constraints possible in high-precision measurements!

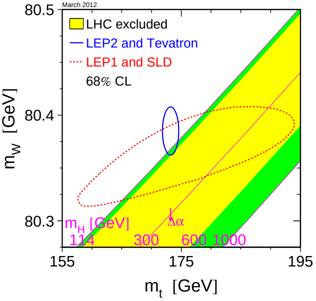




High precision measurements @ LEP

- so: need high precision measurements
  - ↪ 15 observables from LEP-EWWG (m_Z, Γ_Z, ...)
  - ↪ + m_Z, Γ_Z, m_{top} and low-energy observables
- from indirect searches: Higgs mass most likely around 100 GeV
  - ↪ would be still in reach for LEP experiments!





Direct searches at LEP

- since Higgs seemed to be still in reach for LEP:

  ↪ upgraded accelerator to reach up to 206 GeV

- since Higgs coupling increases with particle mass:

  ↪ search for associated production with Z-boson

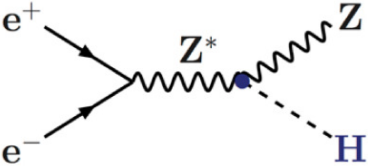
- with $\sqrt{s} \leq 206$ GeV and $m_Z \approx 91$ GeV

  ↪ can only find Higgs if $m_H \approx 115$ GeV

- $\Gamma(H \to b\bar{b}) \approx 70\,\%$

- $\Gamma(H \to \tau^+\tau^-) \approx 8\,\%$

- combine data taken at ALL LEP experiments



➔ reached a lower limit of ≈ 115 GeV

Why the switch from e^+e^- to hadron colliders?

➔ remember Heinrich Hertz:

↪ when charged particles are accelerated, they radiate light

↪ **synchrotron radiation**

➔ particles accelerated in a storage ring:

➔ loose certain fraction of their energy

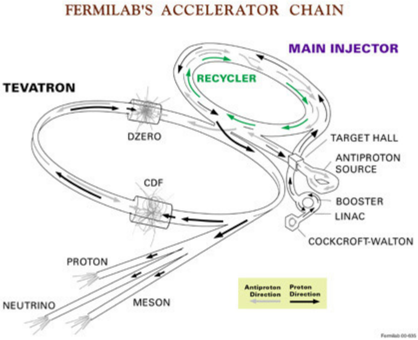
$$\text{Energy loss} \propto \frac{E^4}{m^4} \quad \text{per revol. cycle}$$

⇒ light particles like electrons loose huge amount of energy

⇒ heavy particles like protons emit much less radiation!

Hunt for the Higgs at the Tevatron

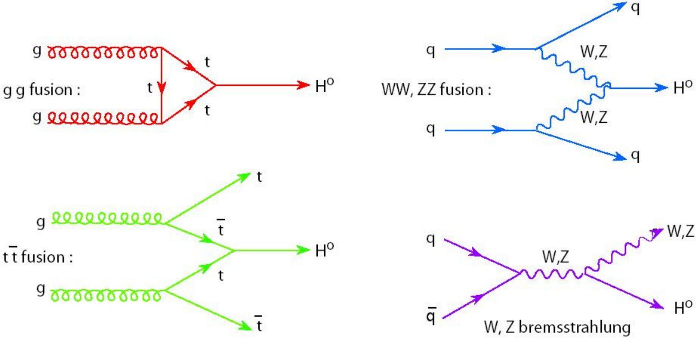
- colliding protons with antiprotons
- from 1986 – 2001: $\sqrt{s} = 1.8$ TeV
- after 2001 upgrade to 1.96 TeV
- discovered the top quark in 1995!
- decommisioned in 2011
- set direct limits on Higgs boson



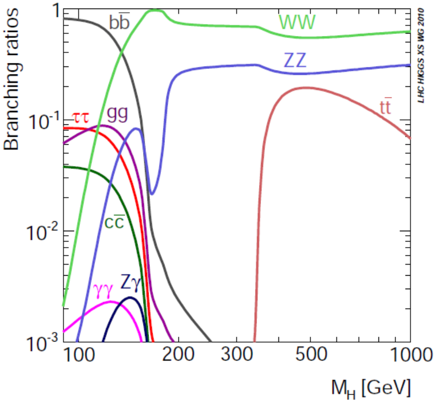
Higgs production channels @ Hadron Colliders

Four main production channels:

- gluon-gluon fusion (*ggF*)
- vector-boson fusion (*VBF*)
- associated production ($t\bar{t}H$)
- Higgs-bremsstrahlung (*VH*)



Higgs decay channels



➔ decay channels depend strongly on mass

➔ at low masses: decay to $b\bar{b}$ dominant

➔ at high masses: phase space for *WW* and *ZZ* opens up

Higgs production at the Tevatron

➔ remember: maximum mass reach of LEP: $\approx$ 115 GeV

➔ Tevatron: centre-of-mass energy: 1.96 TeV

➔ but: not all energy available for production!

➔ proton is composite particle

$\hookrightarrow$ quarks and gluons only carry small fraction x of orig. momentum

$\Rightarrow$ look now at effective centre-of-mass energy:

$$\sqrt{s_{\mathrm{eff}}} = \sqrt{x_1 x_2 s}$$

Assume now $x_1 = x_2 = x$ and $m_H = 125$ GeV, then:

$$x \leq \frac{m_H}{\sqrt{s}} \approx 0.06 \quad (0.016 @ \text{ 8 TeV LHC})$$

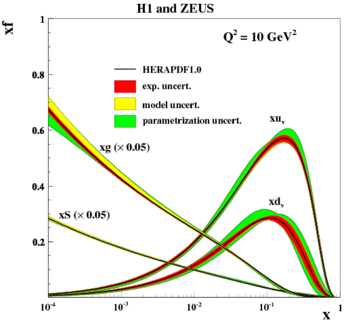
High proton momentum fractions:

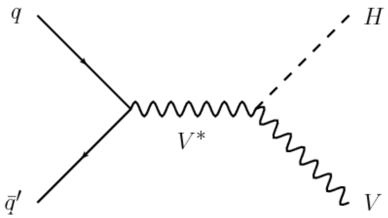
↪ neccessary to produce Higgs boson at Tevatron

↪ dominated by $q\bar{q}$ production

⇒ $q\bar{q}$ more sensitive to heavy Higgs candidates

⇒ dominant production mode at Tevatron: *VH* (Higgs-Strahlung)





Analysis procedure

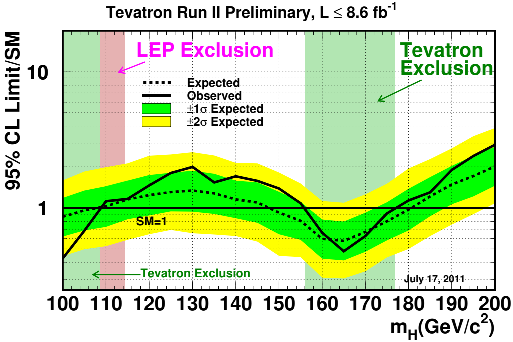
How to approach the search?

- first: need signal and background simulation
- establish an event selection that gives good S/B and S/$\sqrt{B}$
- estimate backgrounds (if possible) based on data

  $\hookrightarrow$ do this in a signal-depleted control region!
- optimize event selection and signal extraction (inv. mass reconstruction, multi-variate analysis methods, etc)

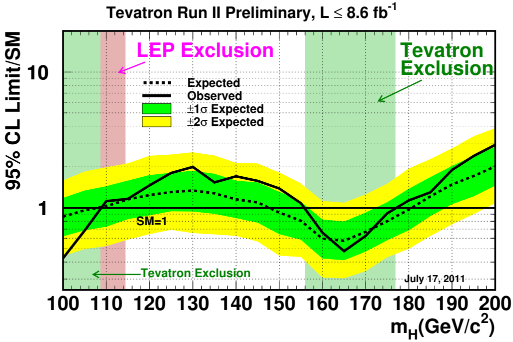
  $\hookrightarrow$ this step is done blind!

How to read a limit plot



- dashed line: expected limit, Bkg only, taken from simulation
- green band: one standard dev, yellow band: two standard dev.
- solid line: observed limit for S+Bkg hypothesis
- y-axis: ratio of cross-section to SM cross-section

How to read a limit plot II



- if observed limit below y == 1: excluded @ 95% CL

  $\hookrightarrow$ applies to green shaded area

- how would a signal look like here?

  $\hookrightarrow$ solid line above y == 1 and outside the yellow band

How to set limits

Now that we can look at the data and do not see a clear signal:

⇒ want to know if we can exclude certain mass hypotheses.

Define log-likelihood ratio (LLR) as test statistic:

$$\mathrm{LLR} = -2\ln\left(\frac{p(\mathrm{data}|H_1)}{p(\mathrm{data}|H_0)}\right)$$

➔ $H_0 \rightarrow$ Null-hypothesis: from simulation only, no signal included

➔ $H_1 \rightarrow$ Test hypothesis: include signal and fit to data

How to set limits II

Need to calculate two values:

Case a)

What is the probability to have an upwards fluctuation in the Bkg so that it looks like Sig+Bkg?

$$1 - \mathrm{CL}_b = p(\mathrm{LLR} \leq \mathrm{LLR}_{\mathrm{obs}} | H_0)$$

Case b)

What is the probability of Sig+Bkg to have a downward fluctuation in data?

$$\mathrm{CL}_{s+b} = p(\mathrm{LLR} \geq \mathrm{LLR}_{\mathrm{obs}} | H_1)$$

When to exclude a signal?

Now:

Could happen that CL_{s+b} is small because experiment is not sensitive to small signal.

$\Rightarrow$ Could accidentally exclude signal when only looking at CL_{s+b}.

Instead: Reject test hypothesis @ 95% C.L. only if:

$$\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{\mathrm{CL}_b} < 0.05$$

If we want to set a limit @ 95% C.L. on signal strength μ:

$\Rightarrow$ We vary μ until $\mathrm{CL}_s = 0.05$.

What is the “look-elsewhere” effect?

Look-elsewhere effect:

The probability to observe a new particle anywhere in mass range under investigation is higher than to observe a local data excess.

⇒ must be taken into account when calculating significance!

➔ In Higgs search: S depends on boson mass, the Bkg does not.
Exact calculation using the LEE can be found here:

▸ Eur.Phys.J. C70 (2010) 525-530

Example: ATLAS discovery paper

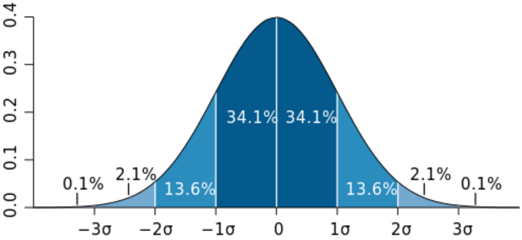
➔ local significance of combination: 5.0 σ

➔ global significance (110–600 GeV): 4.1 σ

➔ global significance (110–150 GeV): 4.3 σ

When do we know we found something?

Compare Bkg only hypothesis (H0) with signal+bkg hypothesis (H1).



Use the same convention between experiments:

- evidence → 3 sigma: 99.73 %
- discovery → 5 sigma: 99.99994 %

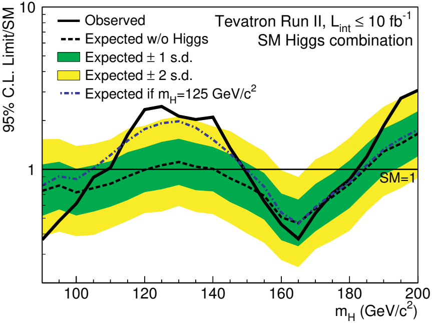
Tevatron combination on full datasets

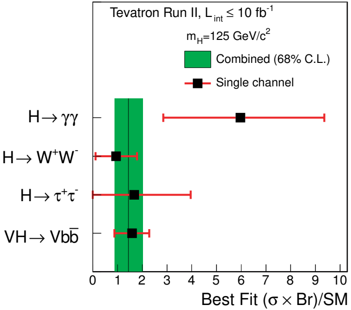
Phys. Rev. D 88, 052014 (2013)

➔ $m_{\mathrm{H}} > 130$ GeV: $H \to W^+W^- \to \ell\nu\ell\nu$ has best sensitivity

➔ $m_{\mathrm{H}} < 130$ GeV: VH with $H \to b\bar{b}, Z/W \to$ lept. has best sensitivity

➔ combine results from $H \to b\bar{b}, W^+W^-, ZZ, \tau^+\tau^-, \gamma\gamma$





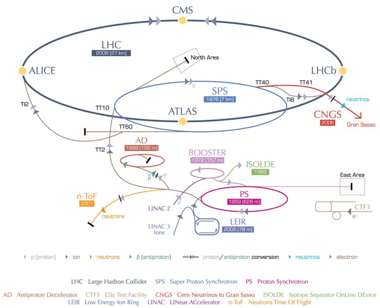
➔ exclude Higgs in range 90–109, 149–182 GeV

➔ excess of data 115–140 GeV: local signif. @ 125 GeV: 3 σ obs.

The Large Hadron Collider

- ➔ colliding protons with protons
- ➔ 1994: LHC proposal approved
- ➔ start in 2008
- ➔ 2011: $\sqrt{s} = 7$ TeV
- ➔ 2012: $\sqrt{s} = 8$ TeV
- ➔ since 2015: 13 TeV!
- ➔ what happened in 2008?

CERN's accelerator complex

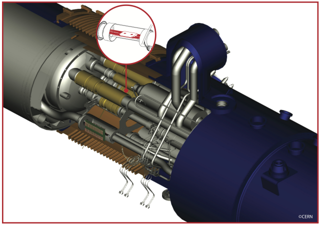


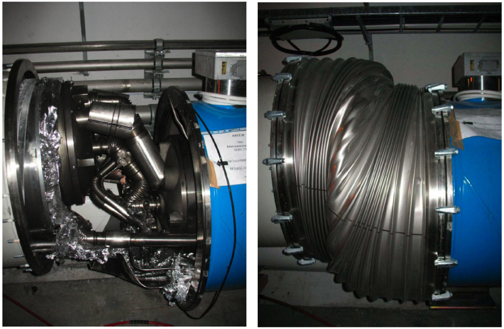
European Organization for Nuclear Research | Organisation européenne pour la recherche nucléaire

© CERN 2008

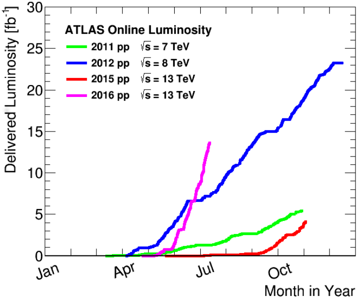
The “Incident” in September 2008

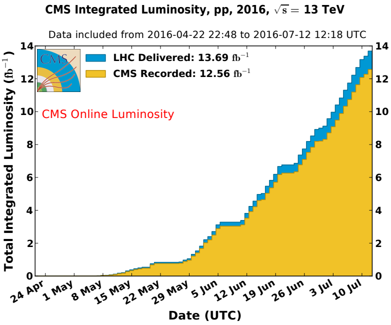
- a few days after the LHC start, a faulty electric connection caused a power abort
- liquid helium used for cooling warmed up
- helium turning into gas expanded quickly and destroyed 53 magnets





How much data do we have?



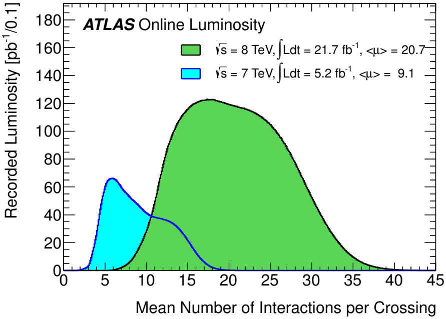


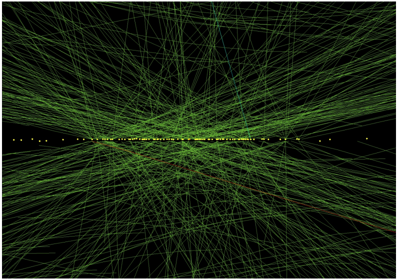
➔ had about 5 fb-1 @ 7 TeV and 6 fb-1 @ 8 TeV for discovery

➔ last year: 3.2 fb-1 of data (also higher cross-sections)

➔ this year: already more than 13 fb-1 !

Experimental challenges: Pileup





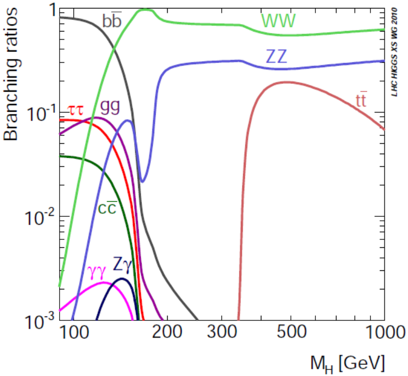
CMS: 78 vertices @ 13 TeV

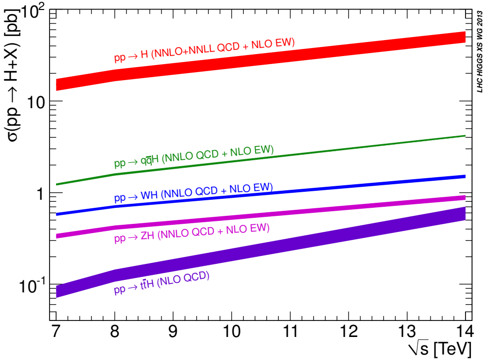
➔ In-time pileup: additional *pp* interactions in same bunch crossing:

↪ increased with beam focus or number of protons in bunch

➔ Out-of-time pileup: add. int. from previous/later bunch crossings

Higgs production at the LHC





➔ *VH* and $t\bar{t}H$ production have heavy particles in FS

↪ processes are very rare

➔ main production channel is gluon-gluon fusion

4th July, 2012

➔ ICHEP conference in Melbourne

➔ at the same time in the CERN main auditorium:

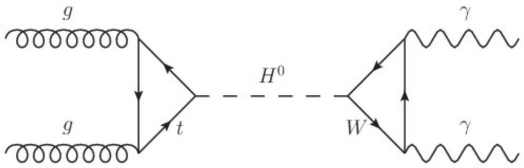
↪ ATLAS and CMS present **observation of a scalar boson**

↪ with Englert and Higgs in the audience

Discovery channels: The $H \rightarrow \gamma\gamma$ channel

- ➔ good mass resolution, have narrow signal peak
- ➔ background is well known and falling
- ➔ background processes: SM $\gamma\gamma$, γ+jet, jet-jet production
- ➔ need diphoton trigger, high E_T isolated photons

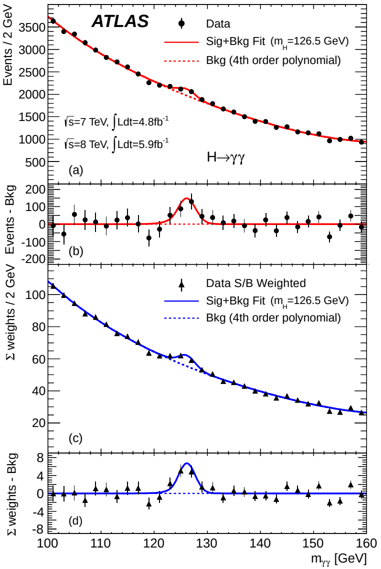
Why is $H \rightarrow \gamma\gamma$ so suppressed?



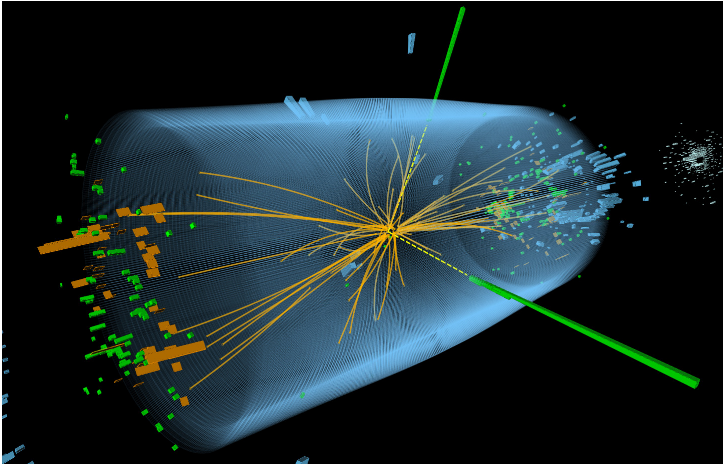
➔ Higgs couples to mass, but photon is massless
⇒ we need a loop for the decay into two photons.

Look closer at $H \to \gamma\gamma$ decay

- low BR $\approx 10^{-3}$
- very clean signature
- great invariant mass resolution
- small background contamination

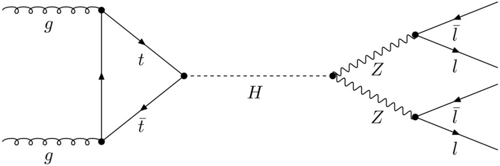


Higgs boson event display (CMS)



Discovery channels: The $H \rightarrow ZZ^* \rightarrow 4\ell$ channel

- ➔ good mass resolution, one or both Z can be off-shell
- ➔ little background in region where Higgs was found
- ➔ main background processes: SM ZZ continuum background



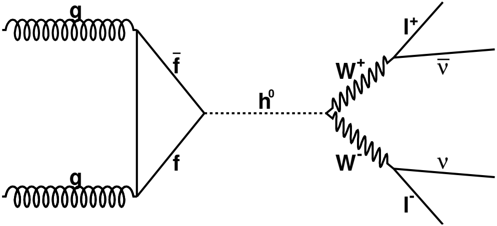
➔ new boson couples to particles with net charge = 0:
$\Rightarrow$ can assume particle is neutral

Discovery channels: The $H \to W^+W^- \to \ell\nu\ell\nu$ channel

➔ channel has good sensitivity

➔ much worse mass resolution due to missing E_{T}

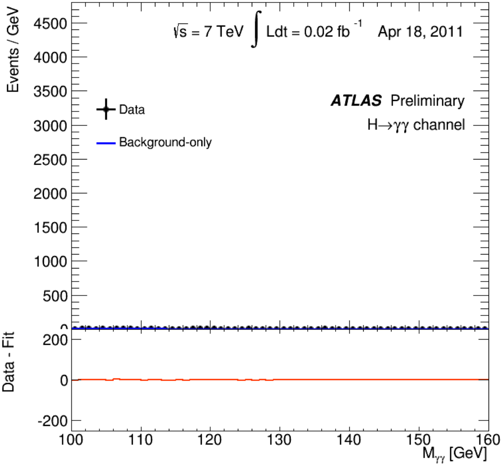
➔ main background processes: SM *WW* production



➔ will see how peaks appear in distributions in the next slides

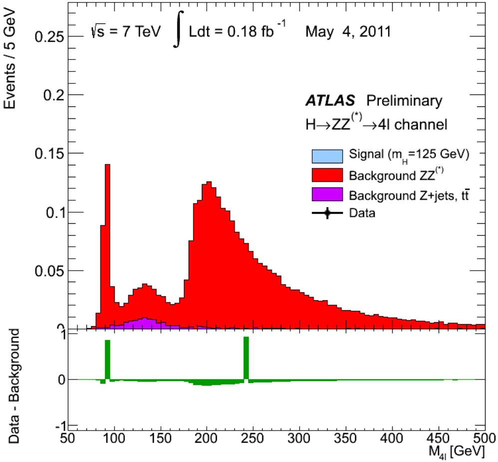
$H \rightarrow \gamma\gamma$ search fast forward

▸ Link ATLAS Webpage



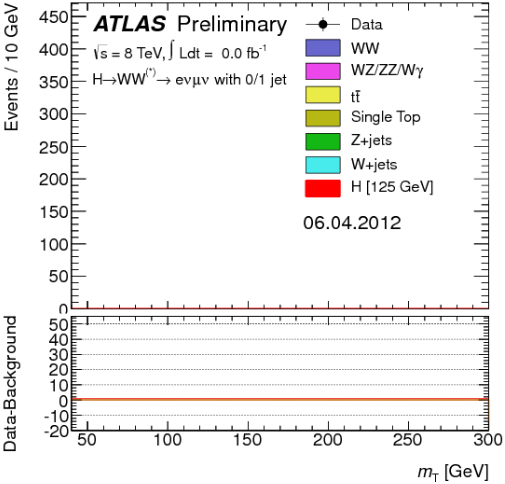
$H \to ZZ^* \to 4\ell$ search fast forward

Link ATLAS Webpage



$H \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$ search fast forward

▸ Link ATLAS Webpage



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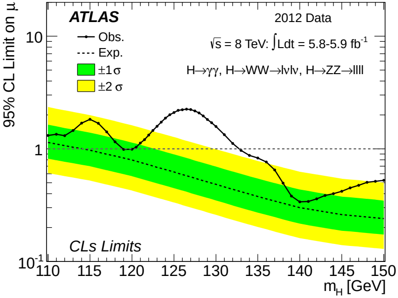
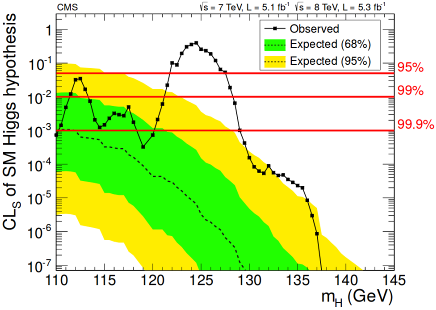
Compare results from both experiments





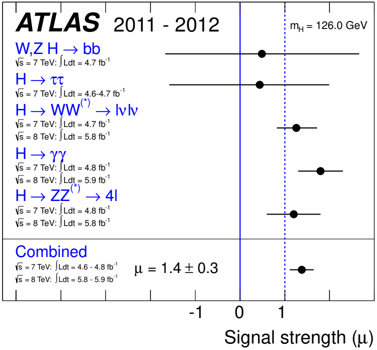
Important to see the same @ both experiments:

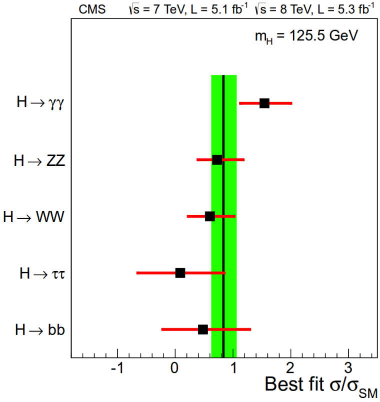
➔ independent measurements at different detectors

➔ both experiments should see the same, if not:

➔ maybe something is wrong (missing syst. or problem with detector/analysis)

Compare results: signal strength



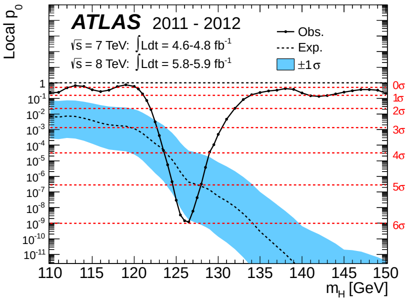


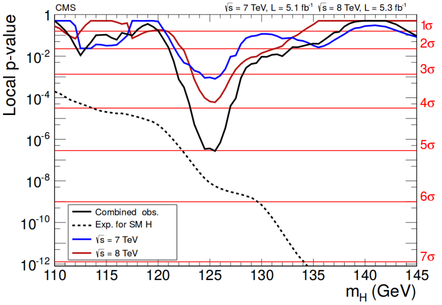
Results for mass measurement:

➔ ATLAS: 126.0 ± 0.4 (stat.) ± 0.4 (syst.) GeV

➔ CMS: 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV

Compare results from both experiments





➔ p_0 shows how consistent the data is with the Bkg-only hypothesis H_0

➔ for both experiments, the p_0 value is not consistent with H_0

Significance of different channels

- $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$:

  ↪ allows to fully reconstruct event

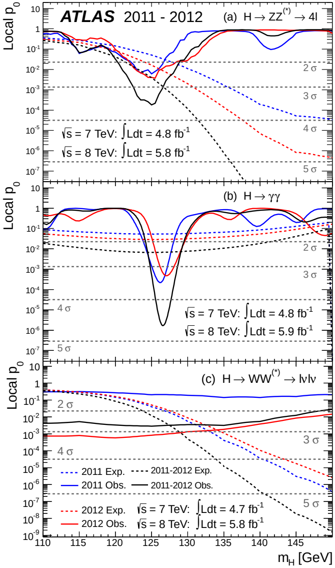
  ↪ good invariant mass resolution

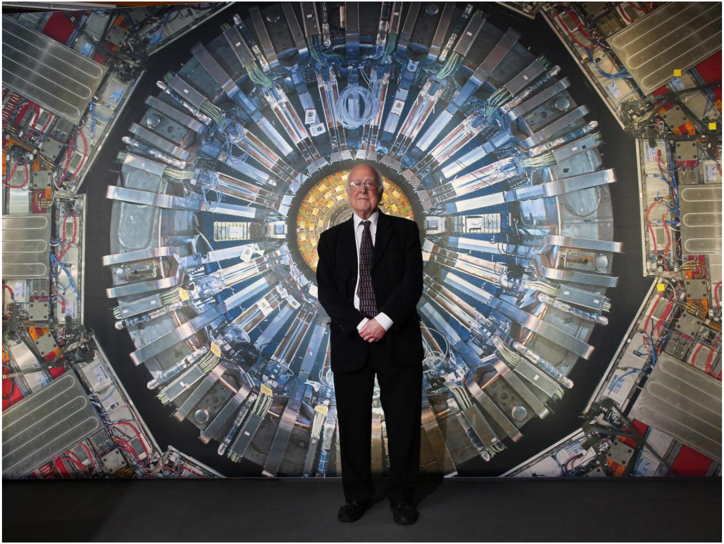
- $H \to WW^* \to \ell\nu\ell\nu$:

  ↪ good sensitivity

  ↪ much worse mass resolution

- important gain from combination with 7 TeV data



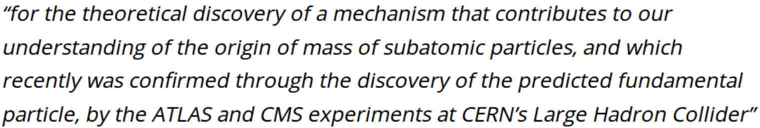


▸ Link article, independent.co.uk

Already in the end of 2013: Nobel prize

▸ Link Photo

From the press release:



"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

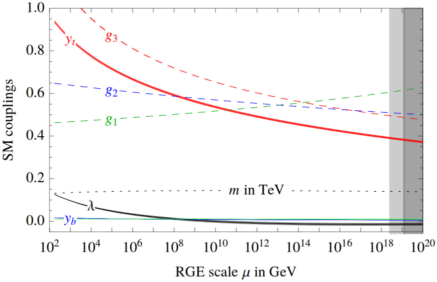
Running quartic coupling

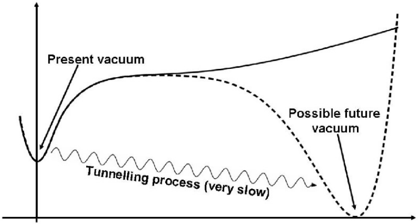
JHEP12(2013)089 arXiv:0807.2601

➔ quartic Higgs-coupling: $\lambda_{\mathrm{HHHH}} = \frac{3m_{\mathrm{H}}^2}{v^2}$

➔ λ is running: slow at high energies

➔ could become negative





➔ if λ negative:

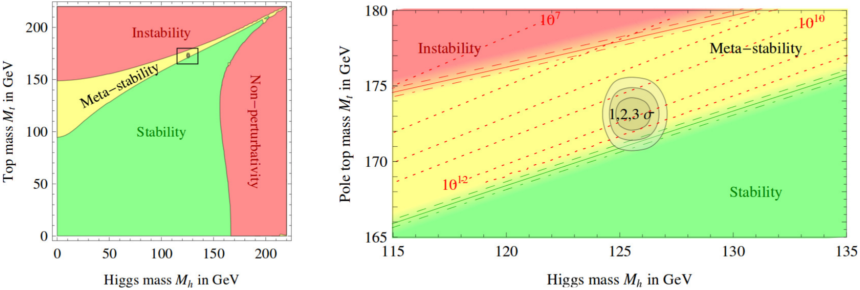
$\hookrightarrow$ vacuum could be unstable

➔ maybe VEV is not global minimum

➔ stability depends on m_{top} and m_{H}

Stabililty of Vacuum

▸ arXiv:1205.6497v2



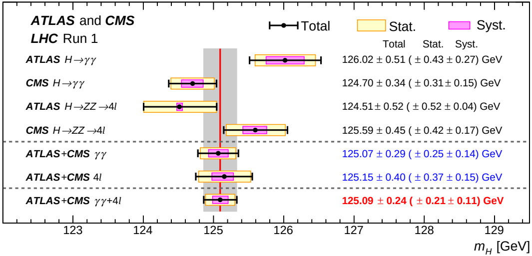
- ↪ vacuum stability strongly depends on top and Higgs masses
- ↪ current mass values: meta-stable, but close to stability
- ↪ meta-stability probably has lifetime of $\mathcal{O}$(lifetime universe)

Combination of mass measurements

▸ Phys. Rev. Lett. 114, 191803

➔ Use $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ results from both experiments.

➔ One or both Zs can be off-shell



➔ Very good relative precision: 0.19 % !

➔ Largest systematics: photon/lepton energy scale and resolution

Remember:

➔ The better we know m_{H}, the better the predictions for cross-sections, branching ratios and couplings!

Have now measured the mass very precisely

With the Higgs mass all couplings are fixed:

➔ coupling to fermions: $g_{Hf\bar{f}} = \frac{m_f}{v}$

➔ coupling to vector bosons: $g_{HVV} = \frac{2m_V^2}{v}$

➔ and: $g_{HHVV} = \frac{2m_V^2}{v^2}$

➔ self-interaction: $g_{HHH} = \frac{3m_H^2}{v}$ and $g_{HHHH} = \frac{3m_H^2}{v^2}$

In addition:

➔ cross-sections and branching fractions of SM Higgs are predicted

$\Rightarrow$ Need to measure those now precisely, and test if consistent with SM predictions!

But: is this really the SM Higgs boson?

Now that we found a new boson, we have to check:

- what are the Higgs properties, are they compatible with the SM?
- discovery channels are couplings to bosons

  ↪ look at couplings to leptons and quarks
- need charge, spin and parity
- measure cross-sections and branching ratios
- find so far undiscovered production channels (for example $t\bar{t}H$)

What do we already know?

a) have very precisely measured mass

↪ but mass not predicted, is free parameter

↪ but mass defines the couplings we want to measure

b) decays into final states with net charge = 0:

↪ particle is neutral

c) decays into two photons: Landau-Yang theorem forbids particles with spin 1 to decay into to photons:

↪ probably not spin 1: need to test, could also be spin 2!

Spin and CP measurements

SM prediction: $J^{\mathrm{CP}} = 0^{++}$

- $C \rightarrow$ charge conjugation operator:

  $\hookrightarrow C|\mathrm{Particle}>=|\mathrm{Antiparticle}>$

- $P \rightarrow$ parity operator:

  $\hookrightarrow P|\vec{x}>=|-\vec{x}>$

Reminder:

➔ Parity is violated in the weak interaction:

↪ *W*-boson only couples to left-handed fermions and right-handed anti-fermions

↪ also small violation of *CP* symmetry

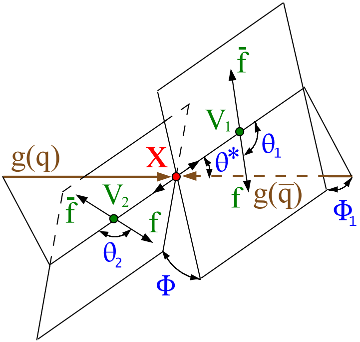
How to measure *CP* eigenvalues?

➔ eigenvalues cannot be measured directly

➔ need information of the angular momenta

➔ need all final state particles to be identified and to be measured with good resolution

$\Rightarrow$ best candidate: $H \rightarrow ZZ \rightarrow 4\ell$!



Hypothesis tests for different scenarios

➔ early analyses: do not have enough stats for full measurement

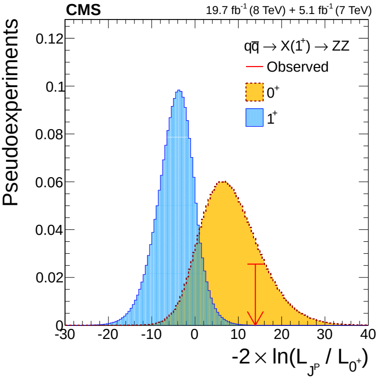
↪ perform hypothesis tests for different spin/parity scenarios

➔ use kinematic information to build discriminant variable

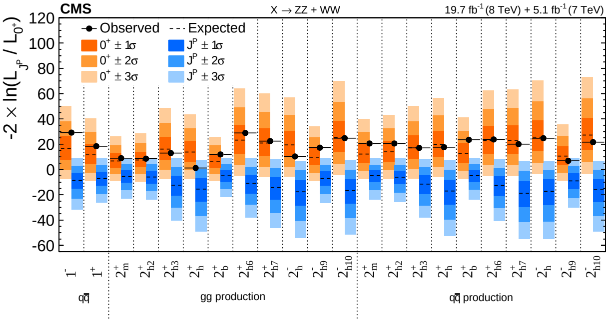
➔ Null-hypothesis: SM configuration 0^+

➔ use test statistics q, throw pseudo experiments for both hypotheses

➔ calculate q-value for data, use CL_s method to get limits



Compare results for all scenarios



➔ most interesting channel: CP= -1:

↪ extensions of the SM like the MSSM predict several Higgs bosons, one of them with CP = -1

↪ so far in agreement with SM prediction

↪ do a full measurement when possible!

What else needs to be tested?

Measurements so far:

➔ looked at mass, spin, parity and charge of boson

But wait!

➔ always assumed that properties belong to exactly one new boson

↪ maybe a superposition of several new, mass degenerated states

➔ do not know if boson couples in same way to leptons and quarks

➔ do not know if boson comples in same way to up/down type quarks

What else needs to be tested?

Measurements so far:

➔ looked at mass, spin, parity andcharge of boson

But wait!

➔ always assumed that properties belong to exactly one new boson

↪ maybe a superposition of several new, mass degenerated states

↪ p-values: 58% (ATLAS), 33 % (CMS) for one-state hypothesis

➔ do not know if boson couples in same way to leptons and quarks

↪ p-value is 79 %

➔ do not know if boson comples in same way to up/down type quarks

↪ p-value is 72 %

⇒ More information in new combination paper: ▸ arXiv:1606.02266

Test the coupling structure ▸ arXiv:1606.02266

- gauge bosons: have same coupling to all fermions:

  ↪ is this the case for the Higgs boson?

- measure Higgs coupling modifiers κ
- take into account possible BSM decays:

  ↪ decays into DM, non-SM decays, ...

  ↪ would change the Higgs width:

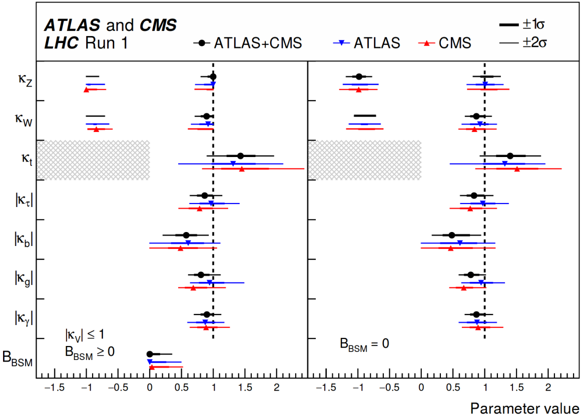
$$\Gamma_H = \frac{\kappa_H^2 \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{B}_{\mathrm{BSM}}}$$

with

$$\kappa_H^2 = \sum \mathrm{B}_{\mathrm{BSM}}^j \kappa_j^2$$

When allowing BSM in loops and decays

arXiv:1606.02266

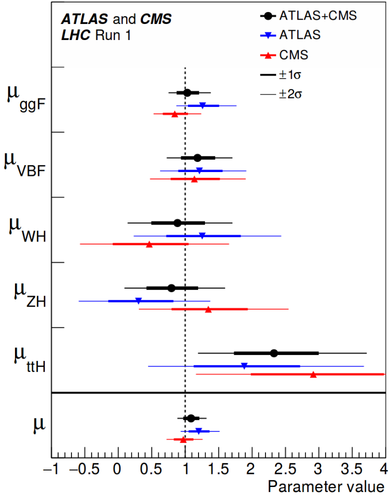


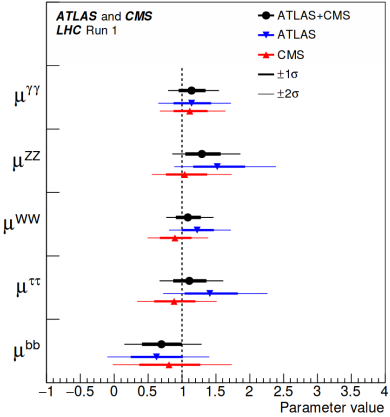
➔ upper limit on B_{BSM}: 0.34 (0.39) obs. (exp.) @ 95% C.L.

➔ p-value: $B_{BSM} = 0$ compatible with SM: 11%

Measurement of signal strength

▸ arXiv:1606.02266





⇒ in good agreement with the SM prediction!

Measurement of coupling structure

arXiv:1606.02266

Check coupling strength vs mass:

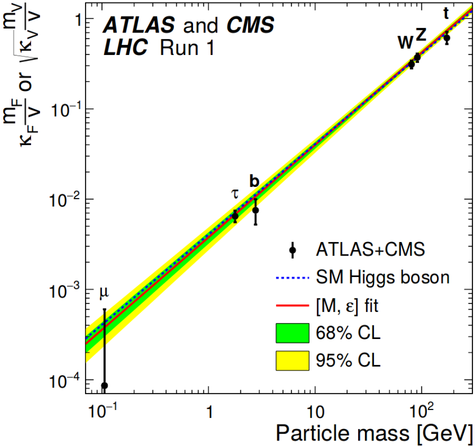
➔ for fermions: $y = k_F \frac{m_F}{246\,\mathrm{GeV}}$

➔ for bosons: $y = \sqrt{k_V}\frac{m_V}{246\,\mathrm{GeV}}$

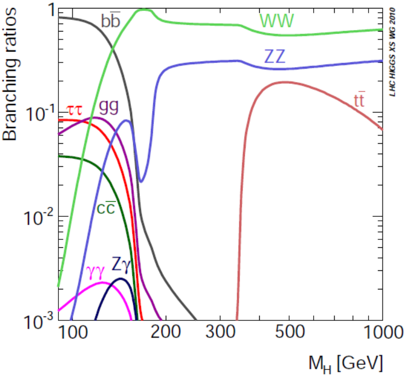
➔ red solid line: fit result

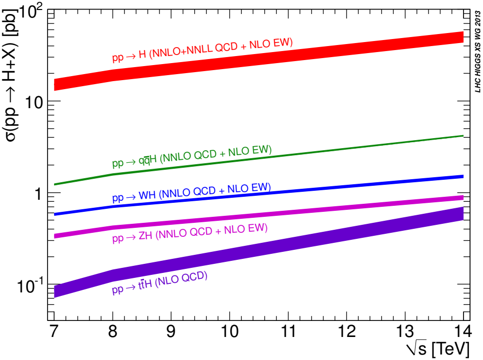
➔ blue dashed line: SM expectation

⇒ In good agreement with the SM!



Reminder: Higgs production at the LHC





➔ *VH* and $t\bar{t}H$ production have heavy particles in FS

↪ processes are very rare

➔ have not observed these two production modes yet

Search for *VH* production

- at 125 GeV: Higgs decays mainly to $b\bar{b}$ (BR = 58 %)
- want to search for $H \rightarrow b\bar{b}$ production:

  $\hookrightarrow$ direct search difficult because of huge multijet background!
- search for associated Higgs production with vector boson
- look at leptonic decays of W and Z:

  $\hookrightarrow$ trigger on leptons and get control on bkg
- main bkg: W/Z+heavy flavour jet, $t\bar{t}$

Search for *VH* in ATLAS

▸ JHEP 01 (2015) 069

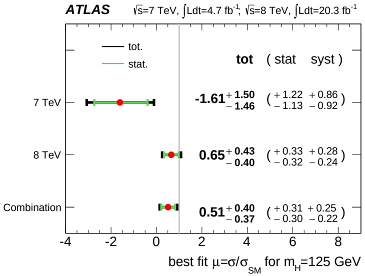
Discriminant variables:

➔ invariant mass of dijet system

➔ Boosted decision trees

➔ 3 lepton categories: 0, 1 and 2 leptons

Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×



Limits:

➔ $\sigma < 1.4\ (2.6)\ \sigma_{SM}$ obs. (exp.) @ 95% C.L.

Motivation: Why search for $t\bar{t}H$?

➔ after discovery of the Higgs Boson:

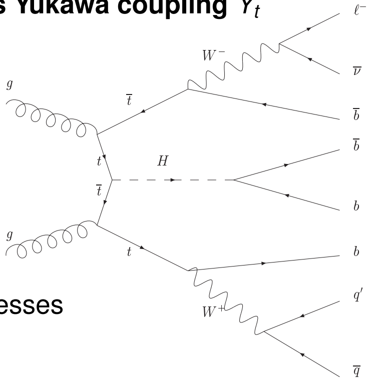
↪ what are its properties?

↪ is it really the SM particle?

➔ important: directly measure the **top-Higgs Yukawa coupling** Y_t

➔ top quark heaviest fermion:

↪ Y_t largest: ≈ 1

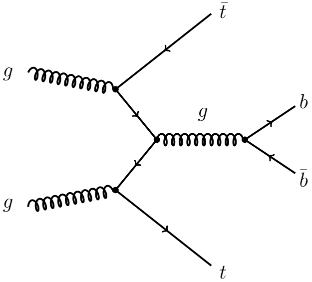


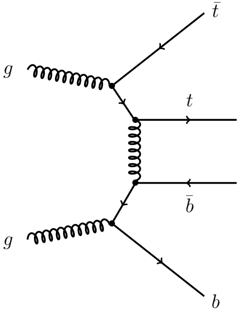
➔ any deviation would be sign for BSM processes

Why $t\bar{t}H$ ($H \rightarrow b\bar{b}$) ?

Challenges:

- largest BR for Higgs decay, **but:**
- irreducible bkg from $t\bar{t}b\bar{b}$
- large uncertainties on $t\bar{t}$+HF





How to cope with irreducible bkg?

➔ exploit as much info as possible

➔ use a NN to get best possible S/B separation

➔ use signal-depleted regions to constrain bkg and unc

➔ combined nuisance parameter fit to all regions

$\hookrightarrow$ analysis here: 8 TeV, 20.3 fb^{-1} ▸ Eur. Phys. J. C (2015) 75:349

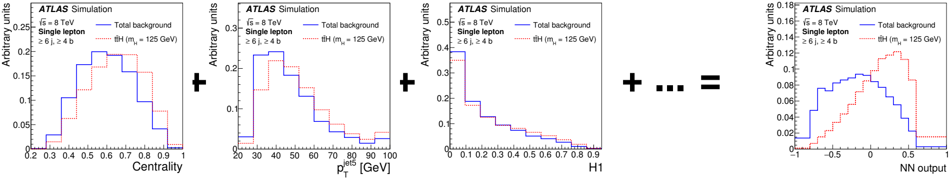
How to find a rare signal?

a) find one “magic” variable that removes most background and keeps large fractions of signal

↪ unfortunately not that easy for most searches ;)

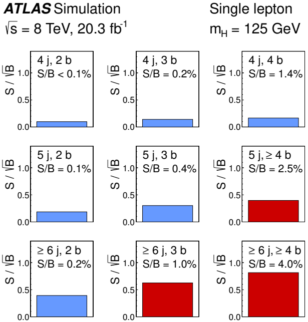
b) gather as much info as possible and combine this to a new variable with good signal and background separation

↪ Multivariate analysis approach: neural net, boosted decision trees etc



Lepton+jets channel

▸ Eur. Phys. J. C (2015) 75:349



Event selection

➔ 1 isolated lepton (25 GeV)

➔ at least 4 jets, 2 *b*-tagged jets

➔ MVA based *b*-tagging

➔ **no** cut on MET/$m_{T,W}$

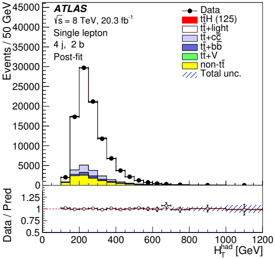
➔ ttbar modelling with Powheg

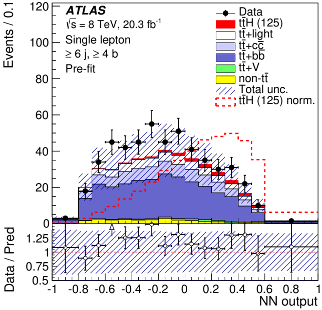
Discriminating variables

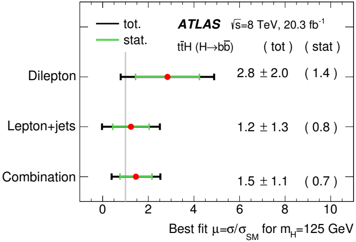
- signal-depleted regions: H_T^{had}
- signal-enriched regions: MVA output

  ↪ input to MVA are 10 variables per region

Results $t\bar{t}H(H \to b\bar{b})$







Final results:

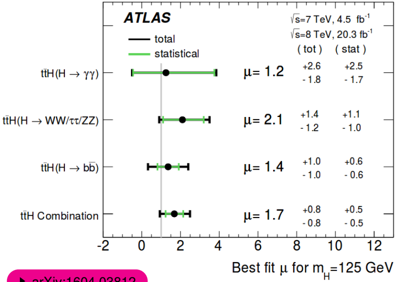
➔ $\sigma < 3.4\ (2.2)\ \sigma_{\mathrm{SM}}$ obs. (exp.) @ 95 % C.L.

➔ Best fit signal strength: $\mu = 1.5 \pm 1.1$

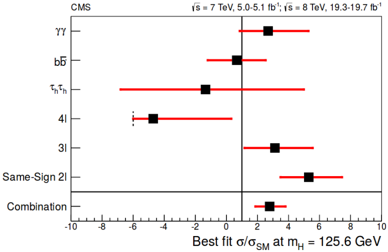
Search for $t\bar{t} + H$ production

▸ Combination note

- ➔ ATLAS+CMS combination @ 8 TeV
- ➔ expected production rate:
- $\hookrightarrow$ 0.129 pb @ 8 TeV (NLO)
- ➔ signal strength: $\mu_{t\bar{t}H} = 2.3^{+0.7}_{-0.6}$



▸ arXiv:1604.03812



▸ JHEP 09 (2014) 087

First 13 TeV results @95 % C.L.:

- ➔ CMS multilepton channel:

▸ CMS-PAS-HIG-15-008

$\hookrightarrow \sigma < 3.3\ (2.6)\ \sigma_{\mathrm{SM}}$ obs. (exp.)

Why are differential measurements important?

- want to test predictions in different parts of phase space
- unfold to parton-level and stable particle level
- allows to compare results from different experiments
- make fiducial measurements

  ↪ allows to test different models

  ↪ helps to constrain systematic uncertainties

Distributions unfolded to:

➔ parton level: Higgs after radiation, but before decay

➔ particle level: stable leptons and jets clustered from stable particles

ATLAS diff. measurements ▸ arXiv:1604.02997

What process are we looking at?

- Channel: $gg \to H \to WW^{*} \to e\nu\mu\nu$, 8 TeV data, 20.3 fb-1

What are the interesting variables?

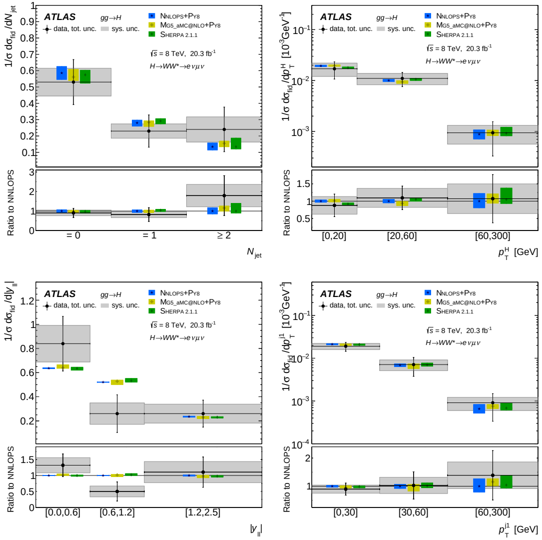
- N_{jet} and p_{T}(lead. jet):
  $\hookrightarrow$ sensitive to higher order pQCD contributions
- p_{T} of Higgs boson:
  $\hookrightarrow$ probe multiple soft-gluon emission
- $|y_{\ell\ell}|$ (corr. to $|y_{\mathrm{H}}|$) :
  $\hookrightarrow$ probe parton density functions

Two kind of comparisons:

a) parton level: compare to fixed order calculation

b) particle level: compare to different MC generator predictions

No deviation from SM prediction found!



Where we stand now

- all measurements shown today and done so far

  ↪ in good agreement with SM

- thats good news... right? Not quite!

  ↪ there are several things that the SM does not describe:

  ↪ does not provide a DM candidate

  ↪ does not explain matter/antimatter assymmetry

  ↪ does not describe strong and EW unification

  ↪ gravity not included, fine-tuning problem, hierarchy problem...

Higgs in Effective Field Theory

➔ There are loads and loads of theories on the market to solve the mentioned problems.

↪ but: a lot of work to test them all

↪ the new physics processes could occur at higher energies than previously studied

➔ one approach: model independent search

➔ new physics could show up in higher order terms to Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

with f_i being Wilson coefficients and Λ being the new physics scale.

Higgs in Effective Field Theory

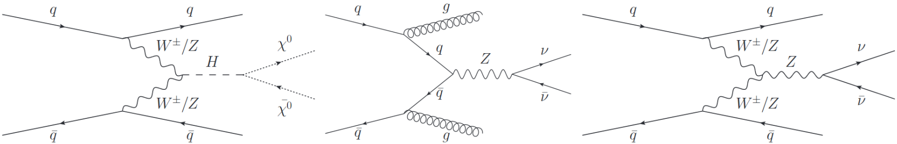
- large number of dimension 6 and 8 operators
- can for example look for anomalous couplings
- would change production rate or show up in deviations of differential distributions
- for good limits on coefficients

  ↪ need large stats and good theory predictions
- papers: ▸ Phys.Lett.B 759 (2016) 672

Invisible Higgs @ ATLAS

▸ JHEP 01 (2016) 172

- ➔ look at Higgs decays into particles that cannot be seen in the detector
- ➔ dark matter candidates or massive, neutral long-lived particles
- ➔ SM decay $H \to ZZ \to 4\nu$ has tiny branching fraction
- ➔ χ is WIMP that only couples to SM Higgs doublet, $m < 0.5\, m_H$

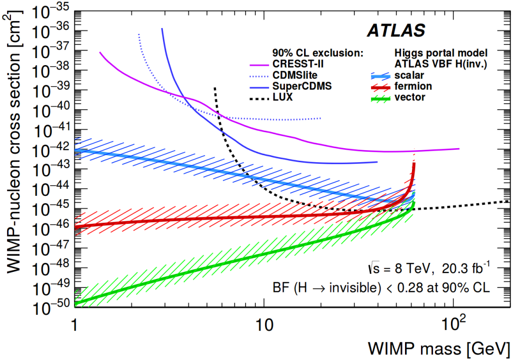


(a) Signal (b) Strongly produced (QCD) Z+jets (c) Weakly produced (EW) Z+jets

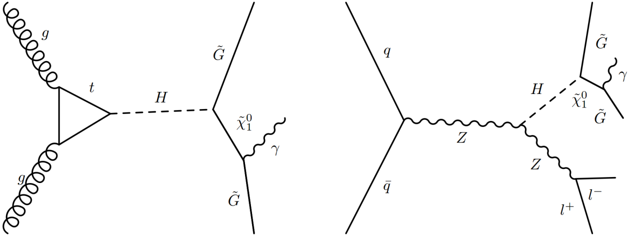
Invisible Higgs @ ATLAS

▸ JHEP 01 (2016) 172

- ➔ $E_T^{\mathrm{miss}} > 150$ GeV, veto events with leptons
- ➔ two well seperated jets, $m_{jj} > 1$ TeV
- ➔ jets not from b or τ (remove top and W background)
- ➔ dominant uncertainties: jet energy scale and resolution



Invisible Higgs at CMS ▸ LINK

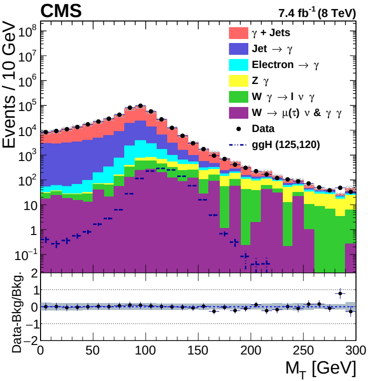


- ➔ search for exotic Higgs, decay in gravitino or neutralino
- ➔ mass for gravitino negligible, neutralino mass large
- ➔ production via *ggH* or *ZH*
- ➔ radiation of one or two photons in final state

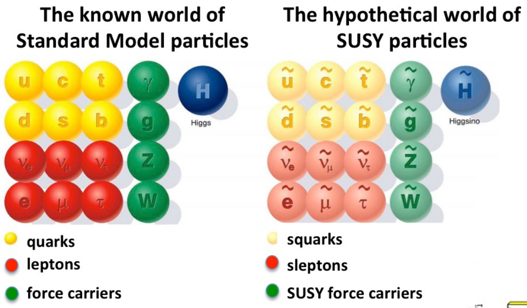
Invisible Higgs at CMS

▸ Phys. Lett. B 753 (2016) 363

- ➔ no deviation from SM found
- ➔ use CL_s methods to set limits
- ➔ large number of BSM models to consider
- ➔ try to set model-independent limits if possible



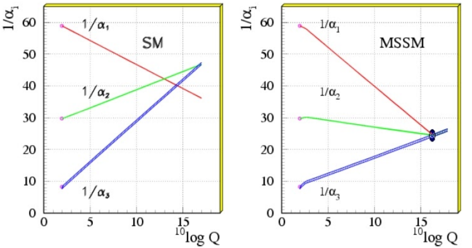
Example MSSM



➔ 5 Higgses predicted:
$h^0, H^0, A^0\text{(pseudo scalar)}, H^+, H^-$

➔ SUSY could provide DM candidate

➔ maybe unification of forces?



New particle found??? Not quite clear...

- as shown in Higgs discovery slides:

  $\hookrightarrow H \rightarrow \gamma\gamma$ channel has clean signature and good mass resolution

- there are several BSM particles predicted that could decay into two photons

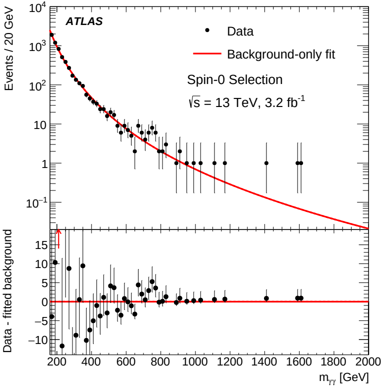
- choose benchmark models to test in data:

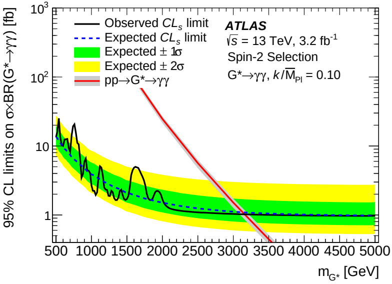
1. particle with spin 2: Randall-Sundrum graviton, would have a very narrow resonance and $m > 500$ GeV
2. particle with spin 0: $m > 200$ GeV, decay products would be isotropically distributed in detector

$H \to \gamma\gamma$ resonances in ATLAS

▸ Subm. to JHEP

- ➔ Bkg: as in discovery search
- ➔ measure in CR from data
- ➔ maximum LH fit to $m_{\gamma\gamma}$ spectrum
- ➔ systematics: nuisance parameters





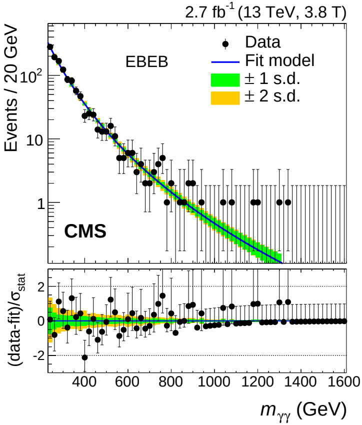
Significance at 750 GeV:

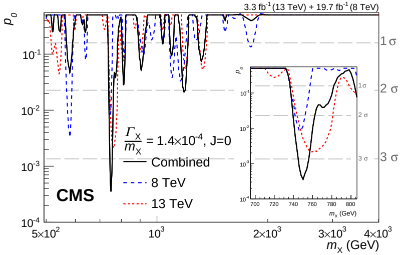
	local	global
spin 2	3.8σ	2.1σ
spin 0	3.9σ	2.1σ

$H \to \gamma\gamma$ resonances in CMS

Acc. by Phys. Rev. Lett.

- ➔ Bkg: as in discovery search
- ➔ combine with 8 TeV
- ➔ look for bump in several detector regions
- ➔ mainly when both photons are in the ECAL barrel





Significance at 750 GeV:

- ➔ local significance: 3.4σ
- ➔ global significance: 1.6σ

Ambulance chasing? ‣ arXiv:1603.01204v1

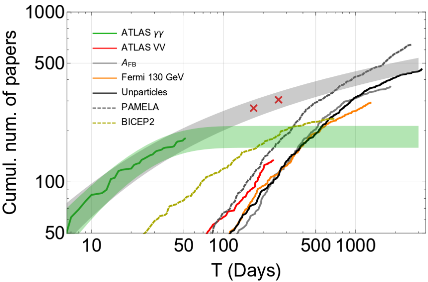
➔ when these results were published in December

➔ number of theory papers published exploded ;)

➔ is important that we work close together with theorists

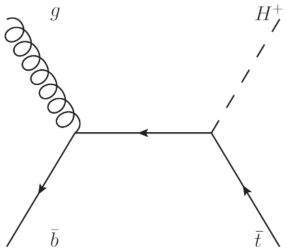
➔ but: also need to be careful, often more data will kill a local excess

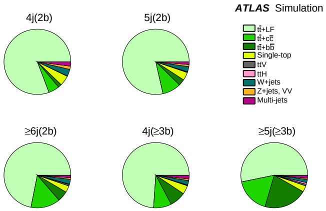
➔ of course exciting, but important to make sure all the background estimates, systematic uncertainties etc are estimated thoroughly



Search for a heavy charged Higgs $H^+ \rightarrow tb$ ▸ JHEP 1603 (2016) 127

- predicted in MSSM or 2HDM
- BR depends on tan β
- associated top H$^+$ production
- 8TeV, 20 fb-1
- train BDT against ttbb

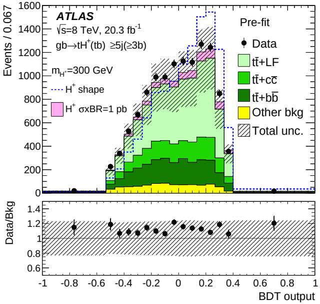


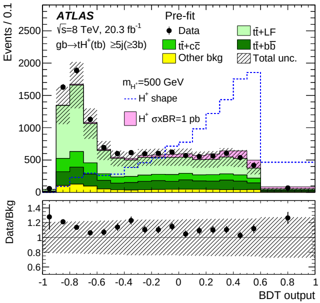


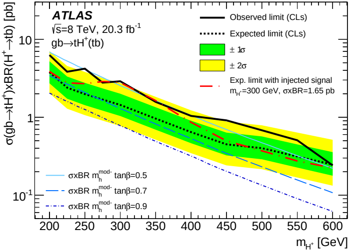
➔ systematics dominated by $t\bar{t}$+HF cross-section, *b*-tagging and JES

➔ include SR and 4 CR in fit

Final results $H^+ \to tb$ ▸ JHEP 1603 (2016) 127







➔ moderate excess in most mass points

➔ large systematics due to $t\bar{t}b\bar{b}$ modelling

What measurements/searches were done so far?

	ggF	VBF	VH	$t\bar{t}H$
$\gamma\gamma$	✓	✓	✓	✓
$ZZ(4\ell)$	✓	✓	✓	✓
$WW(\ell\nu\ell\nu$	✓	✓	✓	✓
$\tau\tau$		✓	✓	✓
bb		✓	✓	✓
$Z\gamma$	✓	✓		
$\mu\mu$	✓	✓		
Invisible	✓	✓	✓	

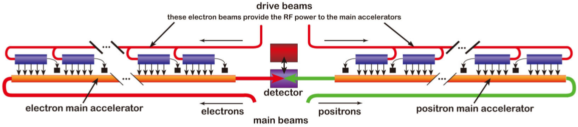
- ➔ + Ht channel
- ➔ + searches for heavy and light H^+, VH resonances, $\gamma\gamma$ resonances
- ➔ + searches for anomalous couplings + ...

⇒ both ATLAS and CMS have a rich Higgs program to test the predictions and (hopefully) find something new!

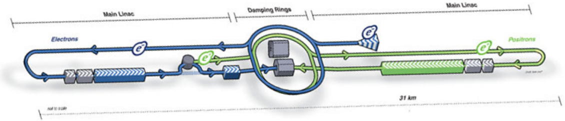
The Higgs at a Linear Collider

Two plans for linear e^+e^- colliders:

CLIC: Compact Linear Collider, up to 3 TeV

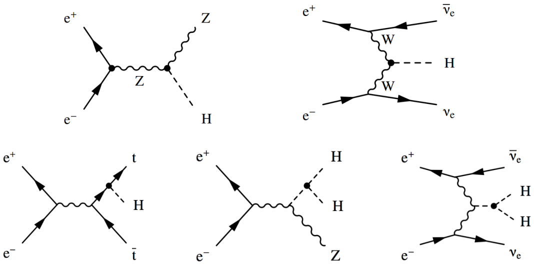


ILC: International Linear Collider, 0.5-1.0 TeV



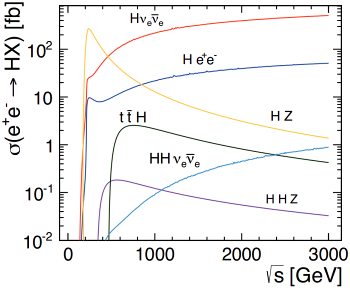
Production mechanisms

▸ MPP-2012-159



➔ for $t\bar{t}H$ and self-coupling:

↪ need CME $\geq$ 500 GeV



➔ at lower CME:

↪ Higgs-strahlung is dominant

➔ from 200 GeV on:

↪ $H\nu_e\bar{\nu}_e$ becomes dominant

The Higgs at an e^+e^- collider

- plans for e^+e^- colliders are still in flow

  $\hookrightarrow$ depends on what LHC will find in the coming years

- advantages:

  $\hookrightarrow$ cleaner production, small backgrounds

  $\hookrightarrow$ acces to all decay modes

  $\hookrightarrow$ different importance of production channels

- allows model-independent measurements of couplings and width

Topics not discussed due to time constraints

- off-shell Higgs, Higgs width
- small production channels like $b\bar{b}H$ and tH
- could not go into details of bkg estimates
- boosted analyses
- future circular colliders: FCC-hh and FCC-ee

Summary

➔ it was a long way from prediction to discovery: $>$ 40 years

➔ first limits set indirectly by EW precision measurements

➔ good collaboration between theory and experiment

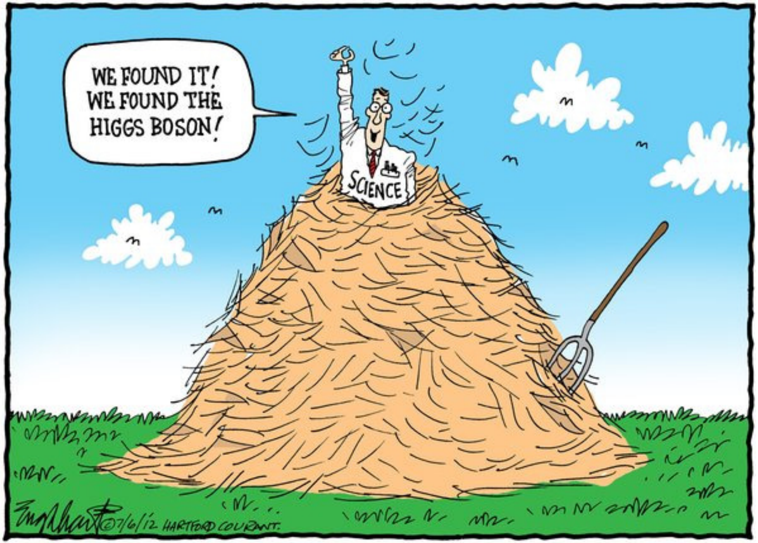
➔ scalar boson was found, looks like the SM Higgs boson so far

➔ but: loads of open questions

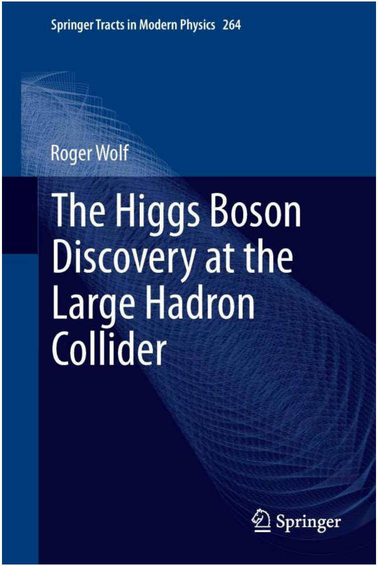
$\hookrightarrow$ naturalness, hirarchy problem, maybe new resonances???

➔ taking more data than ever before at unprecedented energies

➔ Join us to help finding new physics!!!


WE FOUND IT! WE FOUND THE HIGGS BOSON!
SCIENCE
Englehart ©7/6/12 HARTFORD COURANT.

Add. book used for preparation



Springer Tracts in Modern Physics 264

Roger Wolf

The Higgs Boson Discovery at the Large Hadron Collider

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