Karlsruhe Institute of Technology

Institut für Experimentelle Teilchenphysik

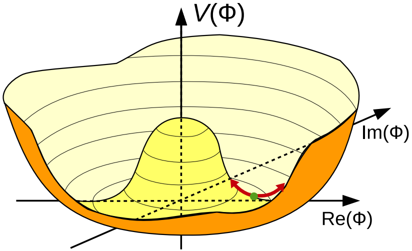
Teilchenphysik II - W, Z, Higgs am Collider

Lecture 11: Search for the Higgs Boson

PD Dr. K. Rabbertz, **Dr. Nils Faltermann** | 7. Juli 2023

The Higgs Boson

- W and Z boson discovered 1983 at the $Sp\bar{p}S$ collider
- Precisely measured the electroweak sector in the following decades, but:
  - Consequence of the Higgs mechanism: **massive scalar particle**
  - What about the Higgs boson?
- Prediction: coupling to gauge bosons and fermions (and self-interaction) with **very specific coupling structure**
- For the rest of the lecture we will focus on the Higgs boson



The Situation in 1975

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Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

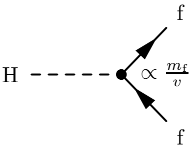
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ 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 par-

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.

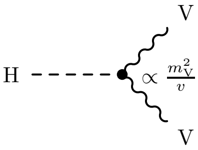
taken from R. Harlander, 2014

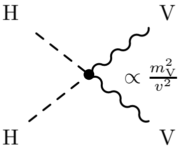
Higgs-Boson Couplings

to fermions:

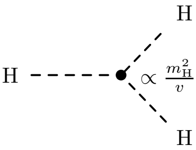


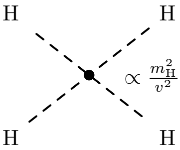
to massive gauge bosons $\mathbf{V = W^{\pm}, Z}$:





self coupling:

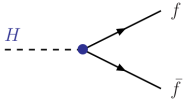




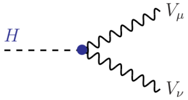
- Coupling terms can be read-off from Lagrangian
  - H is indistinguishable particle: additional combinatorial factor to all amplitudes with more than one H field at vertex
  - At vertex, additional factors i or $-ig^{\mu\nu}$
- Decay width additionally depends on Higgs-boson mass

Higgs-Boson Partial Decay Widths

- Decay to fermions and massive gauge bosons (LO)



$$\Gamma(H \to f\bar{f}) = \frac{1}{8\pi v^2} N_c m_{\mathrm{H}} m_f^2 \beta_f^3$$

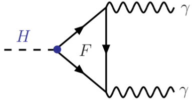


$$\Gamma(H \to \mathrm{VV}) = \frac{1}{32\pi v^2} m_{\mathrm{H}}^3 \delta_V \left(1 - 4x + 12x^2\right) \beta_V$$

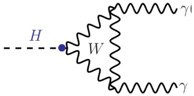
more complicated for virtual V^*
(3-body decay $H \to \mathrm{VV}^* \to V f\bar{f}$)

with $\delta_W = 2$, $\delta_Z = 1$, $x_{f,V} = \frac{m_V^2}{m_{\mathrm{H}}^2}$, $\beta_{f,V} = \sqrt{1-4x}$

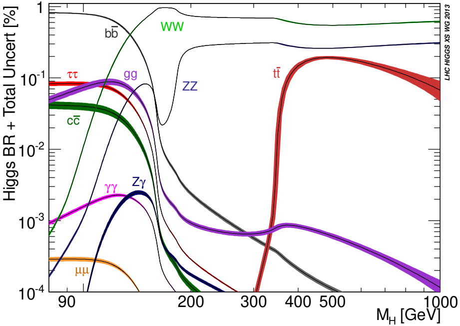
- Decay to photons ($m_{\mathrm{H}} \ll 2m_{\mathrm{t}}, 2m_{\mathrm{W}}$)

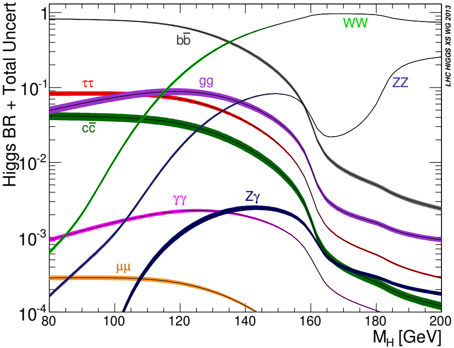


$$\Gamma(H \to \gamma\gamma) = \frac{\alpha_{\mathrm{em}}^2}{256\pi^2 v^2} m_{\mathrm{H}}^3 \Big[\underbrace{\tfrac{4}{3} N_c q_t^2}_{t\text{-quark}} \underbrace{-7}_{W} \Big]^2$$



Higgs-Boson Branching Ratios

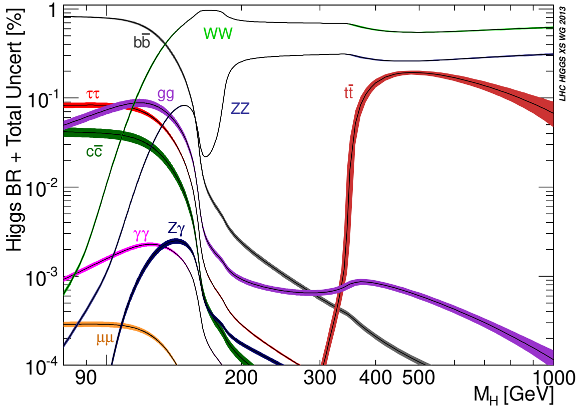




- **Higgs boson couples to mass of particles → Higgs boson mass not known!**
- ≈ dominant decay channels: to heaviest particles (that are kinematically allowed)
  - In case of WW, ZZ: one (or both) can be virtual
  - Also different factors than for fermions

Higgs-Boson Branching Ratios

- $m_H \lesssim 130\,\text{GeV}$: dominated by $b\bar{b}$
- $130\,\text{GeV} \lesssim m_H \lesssim 2m_Z$: $H \to VV(^*)$ starts to dominate



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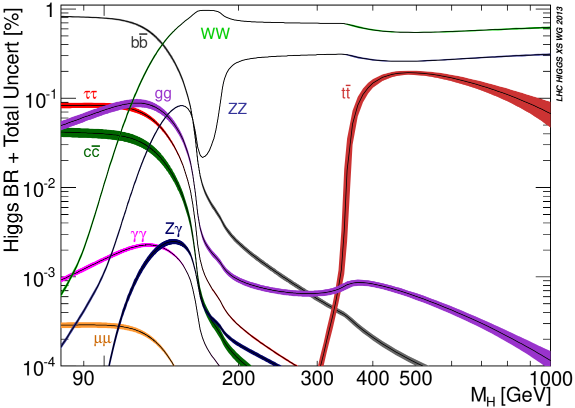
- $130\,\text{GeV} \lesssim m_H \lesssim 2m_Z$: $H \to VV^{(*)}$ starts to dominate
- $m_H \gtrsim 2m_Z$: H decays to $\approx \frac{2}{3}$ to WW and $\approx \frac{1}{3}$ to ZZ ($\propto m_H^3$)
  - Opening of $t\bar{t}$ channel changes little, contribution decreases for larger m_H



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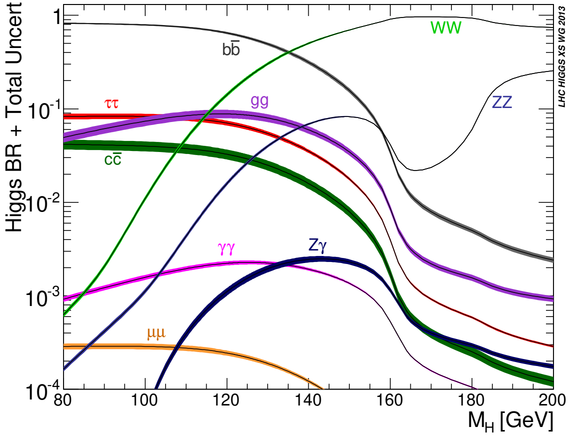

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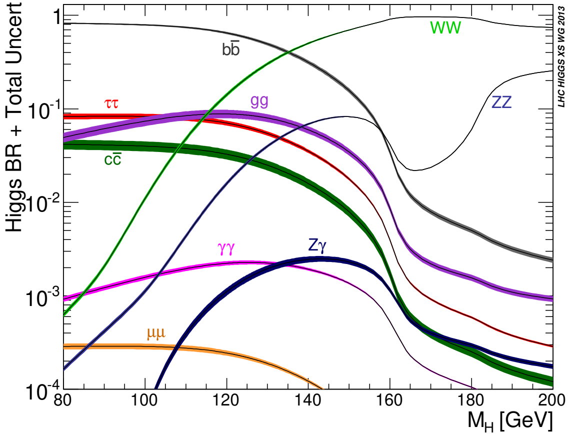
- $130\,\text{GeV} \lesssim m_H \lesssim 2m_Z$: $H \to VV(^*)$ starts to dominate
  - $\Gamma(H \to f\bar{f})$ approximately $\propto m_H m_f^2$
  - $\Gamma(H \to VV)$ approximately $\propto m_H^3$
  - WW entirely dominates between $2m_W < m_H \lesssim 2m_Z$



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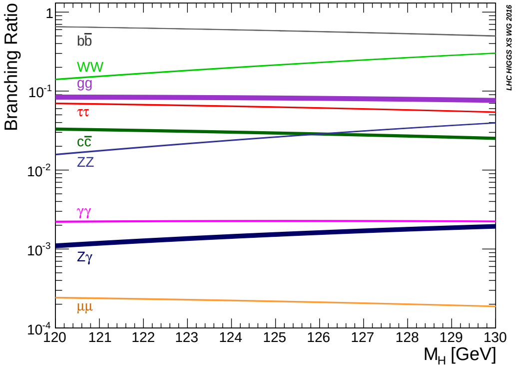
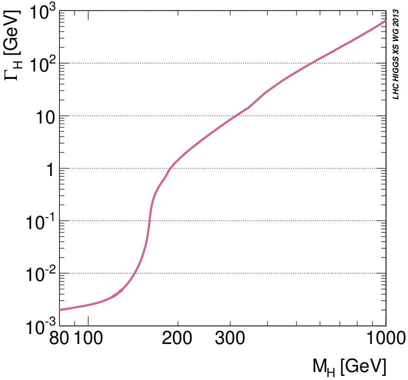


- **At 125 GeV: many open channels — experimentally interesting!**
  - But not all experimentally accessible. . .

Higgs-Boson Total Decay Width



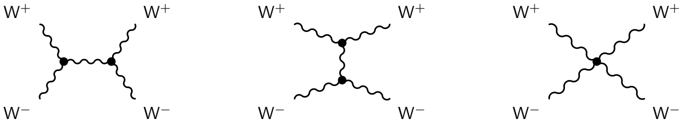
- **Very narrow in low m_H regime**
  - At 125 GeV: 4 MeV
  - Experimentally: entirely dominated by detector and reconstruction effects
- Steep increase with m_H, in particular where $H \rightarrow VV$ opens

Summary of Couplings

- **Consequence of the Higgs mechanism**: massive scalar particle
- Very specific **coupling** to gauge bosons and fermions (and self-interaction), **depending on particle masses**
  - Dominant coupling to heaviest particles
  - Coupling to massless particles ($\gamma\gamma$, gg) via loops
  - $m_{\mathrm{H}} = 125\,\mathrm{GeV}$: many open decay channels
- **Only free parameter in SM Higgs sector: Higgs boson mass m_{H}**
- **As soon as m_{H} known: all Higgs-boson interactions determined!**

Unitarity

- Several Standard Model scattering cross-sections violate unitarity, i. e. become divergent at large $\sqrt{s}$, e. g. WW $\rightarrow$ WW scattering:



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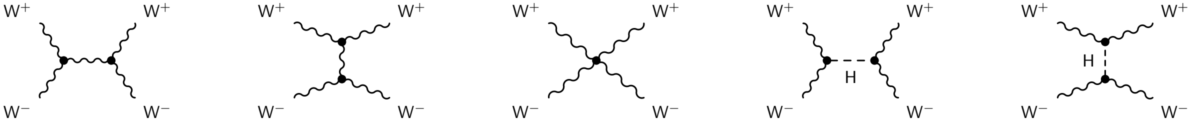

- Adding **contributions from a scalar particle (the Higgs boson) cancels divergencies**, $\sigma \rightarrow$ const for $\sqrt{s} \rightarrow \infty$

> Cancellation of divergencies only if $m_H \lesssim 700\,\text{GeV}$
> (otherwise perturbation theory not valid)

Extrapolation to Higher Scales

- Like the gauge-coupling constants, also the constants μ^2 and λ of the **Higgs potential** are **subject to higher-order corrections**

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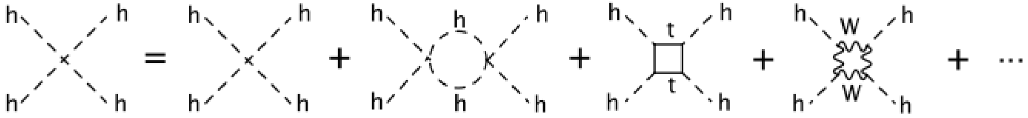
- Contributions from all SM particles that couple to the Higgs boson:



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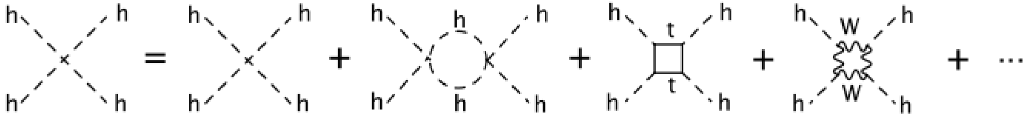

$\rightarrow$ **“running” of μ^2 and λ with energy scale Q**

$$V(\phi) = \mu^2(Q)|\phi|^2 + \lambda(Q)|\phi|^4 \,, \qquad m_H^2 = m_H^2(Q) = -2\mu^2(Q) = 2\lambda(Q)v^2$$

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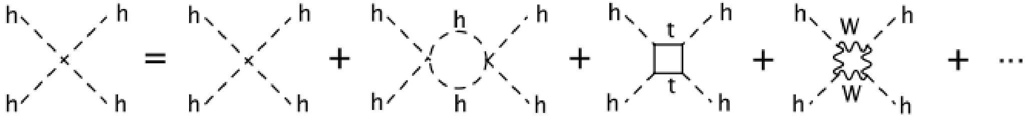

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- **Can the SM (Higgs mechanism) be extrapolated to large scales?**
  - Does $V(\phi)$ behave properly?
  - Does $V(\phi)$ develop a minimum at non-zero $|\phi|$?

Behaviour of $V(\phi)$ at large field-values of $|\phi|$ important: **only λ relevant!**

Running of the Higgs Coupling Constant λ

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- Running of λ given by renormalisation group equation

$$\frac{d\lambda}{d\ln Q^2} = \beta = \frac{3}{4\pi^2}\Big[\underbrace{\lambda^2}_{\text{Higgs}} + \underbrace{\tfrac{1}{2}\lambda y_t^2 - \tfrac{1}{4}y_t^4}_{\text{top quark}} - \underbrace{\tfrac{1}{8}\lambda(3g^2 + g'^2)}_{W^\pm,\ Z\text{ bosons}} + \dots\Big]$$

with β function at 1-loop accuracy

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- **Dominant non-Higgs contributions from processes involving top quarks due to large mass**
  - Large top-quark mass $\leftrightarrow$ large top-Higgs Yukawa coupling y_t
  - Top-Higgs coupling $\propto y_t/\sqrt{2}$

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- **Dominant non-Higgs contributions from processes involving top quarks due to large mass**
  - Large top-quark mass $\leftrightarrow$ large top-Higgs Yukawa coupling y_t
  - Top-Higgs coupling $\propto y_t/\sqrt{2}$
- Subdominant contributions from massive gauge bosons (neglected in the following)

Triviality Bound

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- Running of λ given by renormalisation group equation

$$\frac{d\lambda}{d\ln Q^2} = \beta = \frac{3}{4\pi^2}\Big[\underbrace{\lambda^2}_{\text{Higgs}} + \underbrace{\tfrac{1}{2}\lambda y_t^2 - \tfrac{1}{4}y_t^4}_{\text{top quark}} - \underbrace{\tfrac{1}{8}\lambda(3g^2 + g'^2)}_{W^\pm,\, Z\text{ bosons}} + \dots\Big]$$

- Case: **large** $\lambda \gg y_t, g, g'$ (= heavy Higgs boson since $m_H^2 = 2\lambda v^2$)
  - Higgs boson contribution dominates

$$\frac{d\lambda}{d\ln Q^2} \approx \frac{3}{4\pi^2}\lambda^2(Q^2) \quad \longrightarrow \quad \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3}{4\pi^2}\lambda(v^2)\ln\left(\frac{Q^2}{v^2}\right)}$$

- Relates value of λ at the EWK scale v to its value at a higher scale Q

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- λ increases with Q until it hits pole

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- Relates value of λ at the EWK scale v to its value at a higher scale Q
- λ increases with Q until it hits pole

Require the SM to remain finite up to cut-off scale Λ
$\lambda(\Lambda^2) < \infty$: **upper limit** on $\lambda(v^2)$ and thus on Higgs-boson mass

Stability Bound

- Running of λ given by renormalisation group equation

$$\frac{d\lambda}{d\ln Q^2} = \beta = \frac{3}{4\pi^2}\Big[\underbrace{\lambda^2}_{\text{Higgs}} + \underbrace{\tfrac{1}{2}\lambda y_t^2 - \tfrac{1}{4}y_t^4}_{\text{top quark}} - \underbrace{\tfrac{1}{8}\lambda(3g^2 + g'^2)}_{W^\pm,\,Z\text{ bosons}} + \dots\Big]$$

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  - Top-quark contribution dominates

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- λ decreases with Q until it becomes negative: instable vacuum not bound from below

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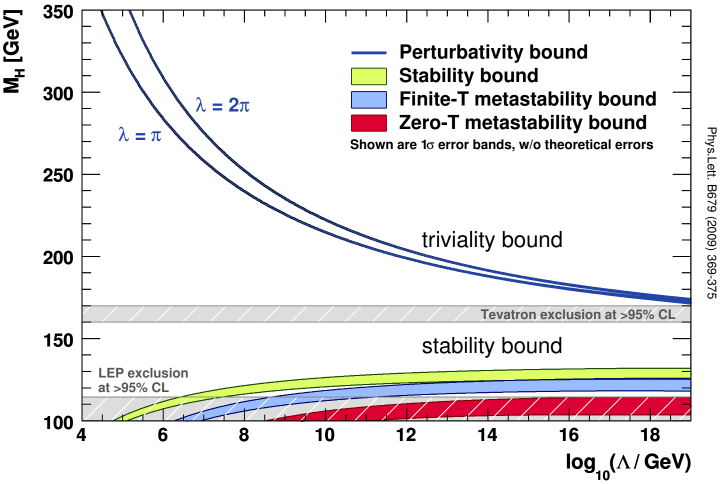
Require $V(\phi)$ to have minimum at finite $|\phi|$ up to cut-off scale Λ
$\lambda(\Lambda^2) > 0$: **lower limit** on $\lambda(v^2)$ and thus on Higgs-boson mass

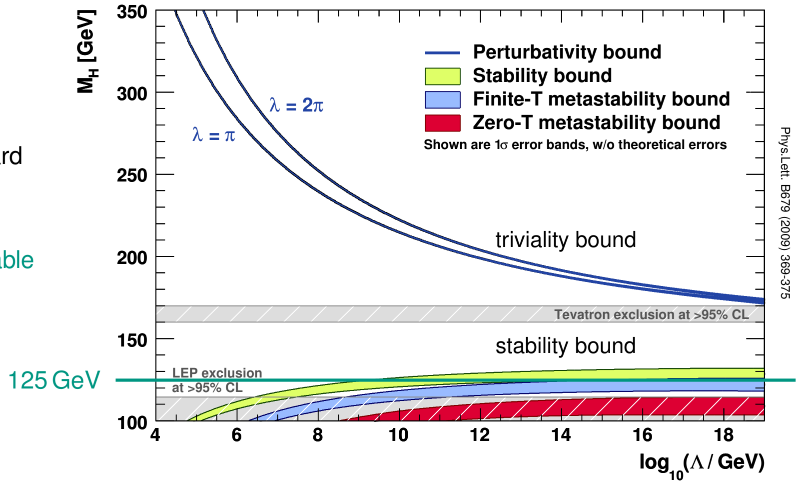
Intrinsic Bounds on Higgs-Boson Mass

- **Cut-off scale** Λ up to which Standard Model should be valid:
  bounds on Higgs-boson mass



Intrinsic Bounds on Higgs-Boson Mass

- **Cut-off scale** Λ up to which Standard Model should be valid: **bounds on Higgs-boson mass**
- With $m_H = 125\,\text{GeV}$: SM in metastable vacuum up to Planck scale (where validity has to end because gravity becomes strong)



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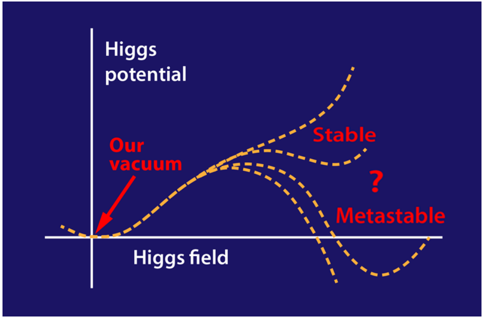
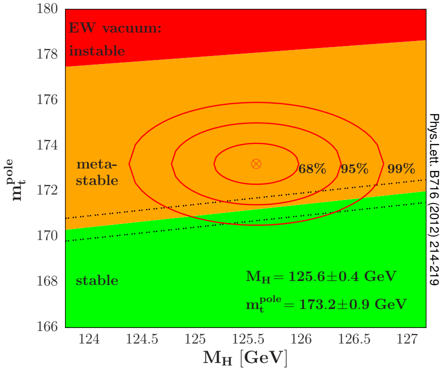
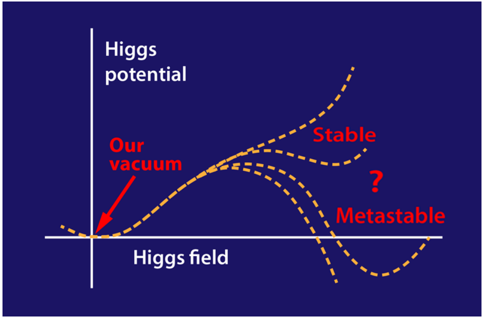
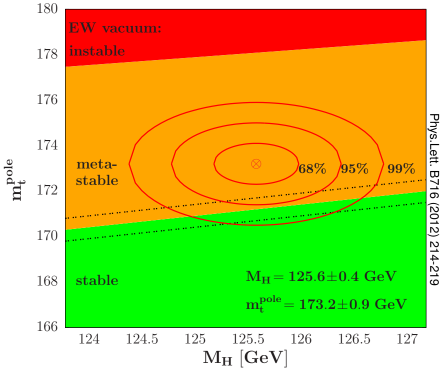




- With $m_H = 125\,\text{GeV}$: **SM in metastable vacuum** up to Planck scale
  - Second minimum below SM vacuum due to higher-order contributions to the Higgs potential
  - Current state can tunnel into absolute minimum, but probability such that lifetime larger than age of the universe

Intrinsic Bounds on Higgs-Boson Mass





- With $m_H = 125$ GeV: **SM in metastable vacuum** up to Planck scale
  - Second minimum below SM vacuum due to higher-order contributions to the Higgs potential
  - Current state can tunnel into absolute minimum, but probability such that lifetime larger than age of the universe
- **Standard Model valid up to Planck Scale?**
  - Uncertainties due to **uncertainty on top-quark mass**

Phenological Summary

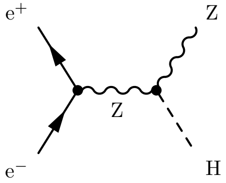
- **Higg-boson mass m_H not predicted** by the SM Higgs-mechanism
- But **intrinsic upper and lower bounds** from consistency arguments in running of Higgs self-coupling parameter λ with energy scale
  - **Perturbativity (triviality)**: upper bound
  - **Stability of vacuum**: lower bound
  - Bounds depend on energy scale up to which SM is assumed to be valid (appearance of new physics beyond the SM can change the picture)
- With $m_H = 125\,\text{GeV}$ and Standard Model valid up to Planck scale: **metastable vacuum**

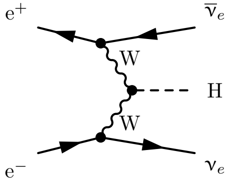
Search Overview

- Higgs boson **mass range limited** by theoretical arguments (perturbativity, triviality, vacuum stability) $\rightarrow$ roughly **100 GeV to 1 TeV**
- **Strategies** to search for the Higgs boson (or any new particle in general):
  - **Direct search** for Higgs production and decay at colliders $\rightarrow$ limited by centre-of-mass energy and luminosity
  - Search for **indirect effects** in higher-order corrections ("loops") $\rightarrow$ sensitive to much higher Higgs masses but possibly model-dependent
- Brief **history** of Higgs boson searches
  - **LEP** (1989–2000), **SLC** (1989–1998): **direct** and **indirect** searches
  - **Tevatron** (1992–1996, 2001–2011): **direct** searches
  - **LHC** (Run I 2010–2012): **direct** searches $\rightarrow$ **discovery**

Production Processes at LEP (e^+e^-)

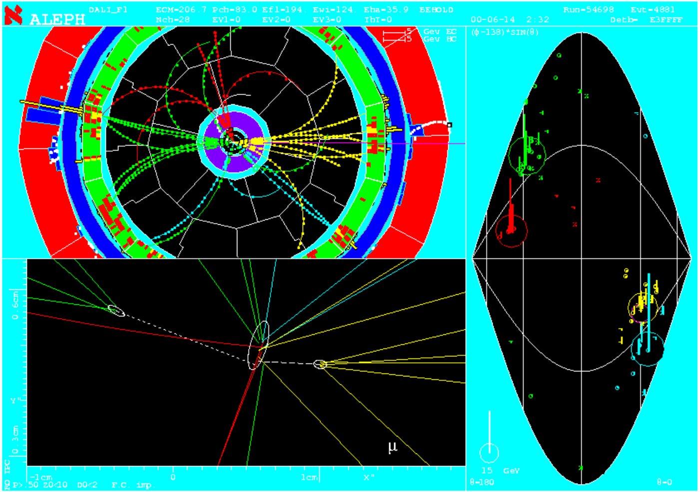
- **LEP 1**: centre-of-mass energy ≈ 91 GeV (Z pole)
  - Only lower limits from non-observation of Z decays including Higgs bosons
  - Exclusion of **light scalar particles**
- **LEP 2**: nominal centre-of-mass energy increased from 161 GeV (WW production threshold, 1996) and 209 GeV (limit of LEP cavities, 2000)
  - Production channels: **Higgs-strahlung** (most sensitive), $\nu\nu$H (WW fusion)





  - Access up to $\boxed{m_H \approx \sqrt{s} - m_Z \approx 118\,\text{GeV}}$
  - Preferred decay channels: $H \to b\bar{b}/\tau\tau$, $Z \to ll/q\bar{q}/\nu\nu$

Higgs-Boson Candidate at ALEPH



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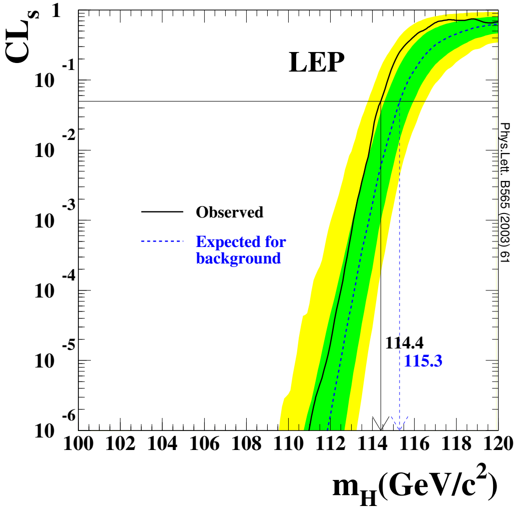
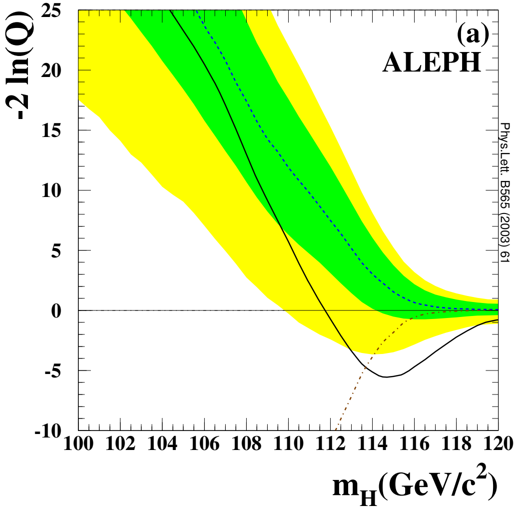
Process: $e^+e^- \to ZH \to q\bar{q}b\bar{b}$

The Final Word from LEP



- Combination of data from all four experiments (ALEPH, DELPHI, L3, OPAL)
- Observed (expected) 95 % C.L. limit: $\boldsymbol{m_H > 114.4\,\text{GeV}\ (115.3\,\text{GeV})}$
- Reminder, theoretical reach: $m_H \approx 118\,\text{GeV}$

A Side Note...

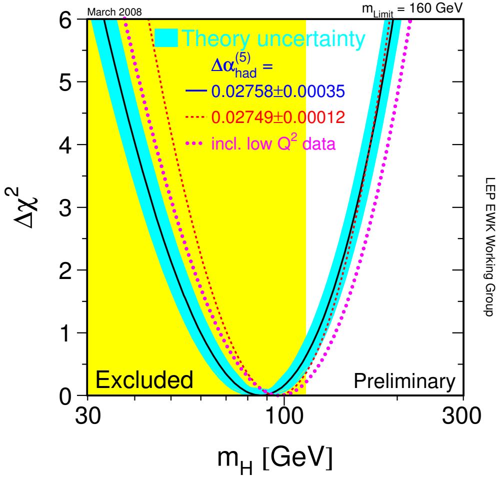


- Small excess observed at $m_{\mathrm{H}} \approx 115\,\mathrm{GeV}$ by one (ALEPH) of the four experiments at the end of LEP-2 Run
- Discussion to extend LEP-2 Run for a few more months to investigate
  - Large additional operation costs, no budget
  - Delay in decommissioning and thus delay of building the LHC
- Plans not pursued in the end
  - Turned out to be the correct decision more than a decade later
  - Higgs boson heavier, not in reach of LEP

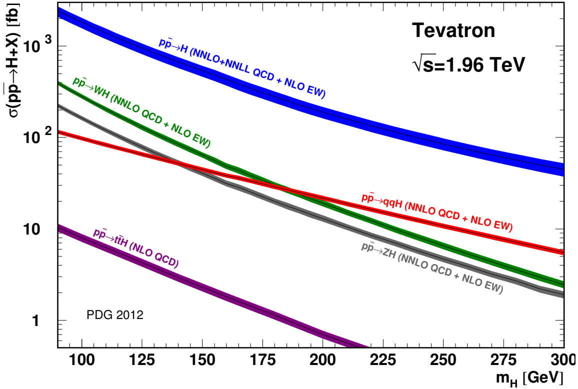
Constraints on Higgs-Boson Mass

- Motivation for a light Higgs boson also from electroweak precision measurements
- **Global fit:**
  - LEP Electroweak Working Group (Spring 2008): before the LHC is turned on
  - 18-parameter χ^2 fit: Z pole + W boson + top quark
  - No inputs from direct Higgs boson searches
- Results
  - Best-fit Higgs mass: $\boldsymbol{m_\mathrm{H} = 94^{+29}_{-25}}$ **GeV**
  - **Lighter** Higgs boson preferred
  - **Logarithmic** dependence: m_H only weakly constrained

"Blue Band Plot": Higgs mass limits (before LHC)



Higgs Production at the Tevatron ($p\bar{p}$)

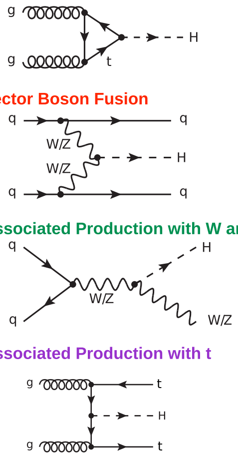


Gluon-Gluon Fusion

Vector Boson Fusion

Associated Production with W and Z

Associated Production with t

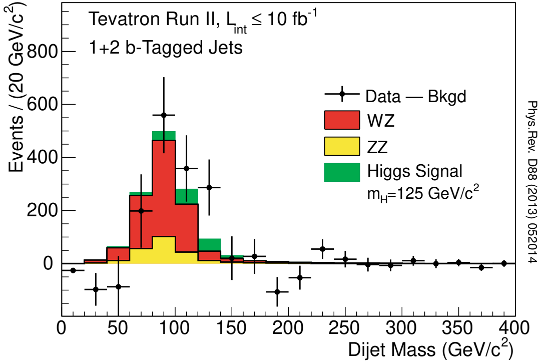


- Cross section **steeply falling** with m_H
  $\rightarrow$ only accessible for **light** Higgs boson
- gluon-gluon fusion: large QCD background
  $\rightarrow$ preferred: associated **WH production**

Decay Channels at the Tevatron

- Relevant Higgs-boson **decay channels** at the Tevatron:
  - $\mathrm{H} \to \mathrm{b\bar{b}}$: identification via b-tagging, but large QCD background
  - $\mathrm{H} \to \tau\tau$: large background from QCD (and $\mathrm{Z} \to \tau\tau$)
  - $\mathrm{H} \to \mathrm{WW}$: sensitivity for $m_\mathrm{H} = 2m_\mathrm{W} \approx 160\,\mathrm{GeV}$, works with gg fusion
  - $\mathrm{H} \to \gamma\gamma$: very clean but small branching fraction, works with gg fusion
- Most sensitive channels: **VH($\mathrm{b\bar{b}}$)**
  - $\mathrm{p\bar{p}} \to \mathrm{WH} \to \ell\nu\mathrm{b\bar{b}}$
  - $\mathrm{p\bar{p}} \to \mathrm{ZH} \to \ell\ell\mathrm{b\bar{b}}$

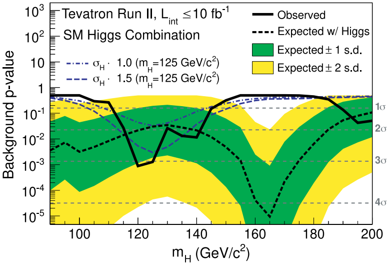
dijet mass in VH($\mathrm{b\bar{b}}$) after background subtraction



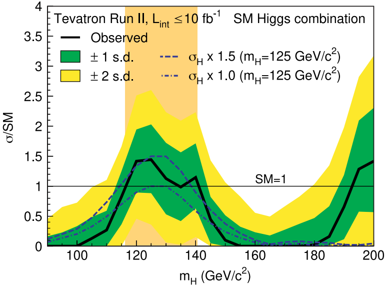
The Final Word from Tevatron (July 2nd, 2012)

- **Excess** observed in Tevatron data
  - Up to 3 σ for **115 GeV** $<$ $\boldsymbol{m_H}$ $<$ **140 GeV**
  - Compatible with approx. **1.5** $\times$ $\boldsymbol{\sigma_{SM}}$

Background-Only *p* Value



Best-Fit Signal Cross Section



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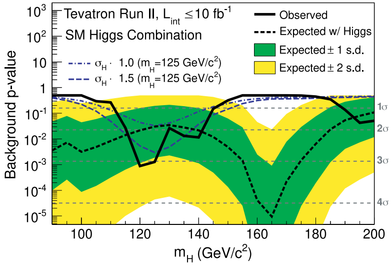
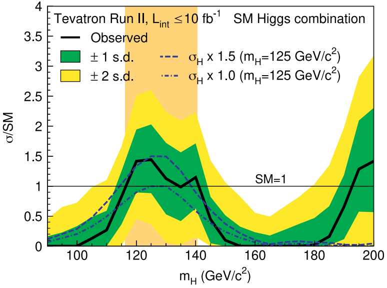
  - Up to 3 σ for **115 GeV** $<$ $\boldsymbol{m_H}$ $<$ **140 GeV**
  - Compatible with approx. **1.5** $\times$ $\boldsymbol{\sigma_{SM}}$
- 95 % C.L. **exclusion** from Tevatron data
  - 90 GeV $< m_H <$ 109 GeV
  - 149 GeV $< m_H <$ 182 GeV

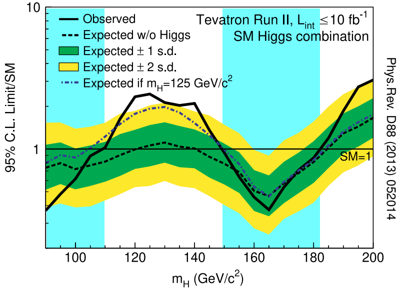
Background-Only *p* Value



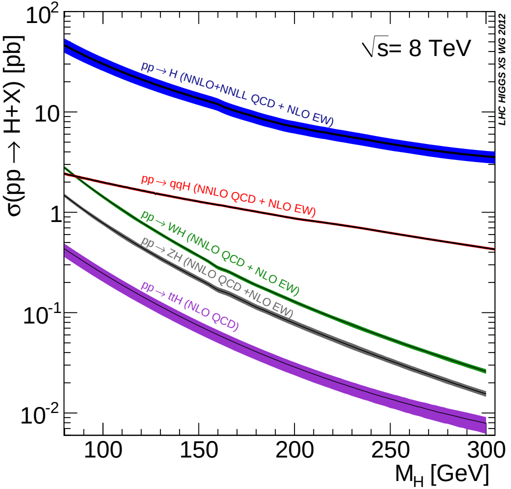
Best-Fit Signal Cross Section



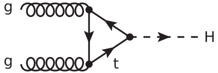
Bayesian 95% CL Upper Limit



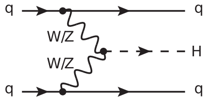
Higgs Production at the LHC



Gluon-Gluon Fusion



Vector Boson Fusion



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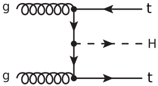
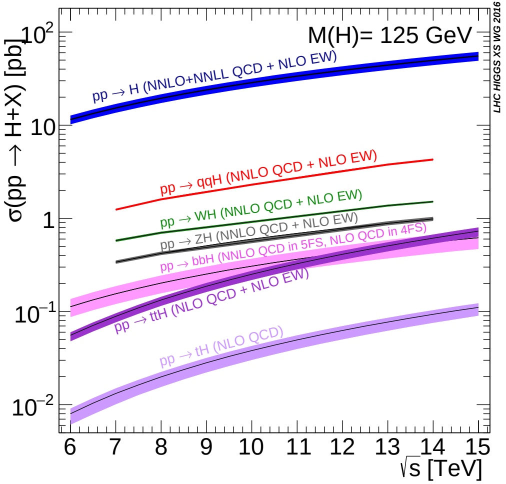
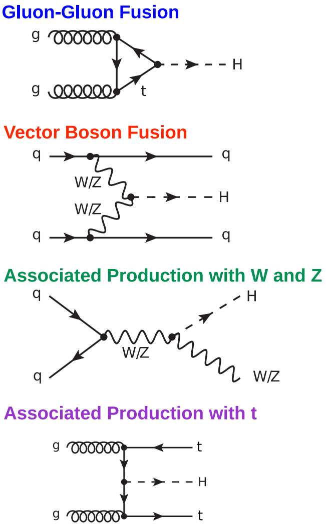


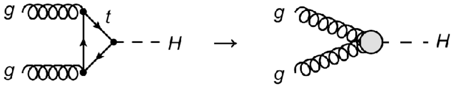
Higgs Production at the LHC



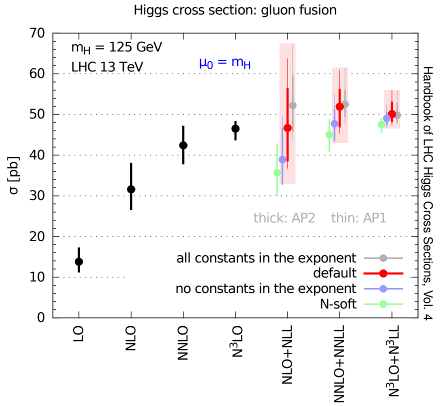


Example: gg $\rightarrow$ H

- State-of-the-art for gg $\rightarrow$ H inclusive cross section: NNNLO QCD and NLO electroweak (EWK) corrections[1]
  - **NNNLO** in effective field theory (EFT) with $m_t \rightarrow \infty$, rescaled to exact LO result $(\sigma_{ex}^{LO}/\sigma_{EFT}^{LO})$



  - Corrections: massive quarks, EWK $\mathcal{O}(\alpha^3)$, mixed QCD-EWK $\mathcal{O}(\alpha\alpha_s^3)$
  - Result for $m_H = 125\,\text{GeV}$ at 13 TeV



$$\sigma(gg \rightarrow H) = 48.58\,^{+2.22}_{-3.27}\,(\text{theory}) \pm 1.56\,(\text{PDF} + \alpha_s)\,\text{pb} \quad \rightarrow \quad \text{about } \mathbf{6\,\%\ uncertainty}$$

[1] Details: (C. Anastasiou et al., JHEP 1605 (2016) 058) and Handbook of LHC Higgs Cross Sections, Vol. 4

Most Important Analysis Channels

Karlsruhe Institute of Technology

Rationale: favourable combination of cross section times branching ratio,selection efficiency, signal-to-background ratio, resolution, . . .

Production	Decay	Remark
$gg \to H$	$H \to ZZ(^*) \to 4\ell$	excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to \gamma\gamma$	small branching fraction but excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to WW(^*) \to \ell\nu\ell\nu$	large production cross section but poor mass resolution (two neutrinos)
$gg \to H$ $qq \to qqH$	$H \to \tau\tau$	decay into fermions with large branching fraction but large QCD background
$qq \to VH$	$H \to bb$	large QCD background → additional tag through (leptonic) vector-boson decay
$gg \to ttH$ $gg \to tHq/tHW$	$H \to bb, \gamma\gamma,$ multi-leptons	access to top-quark Yukawa coupling

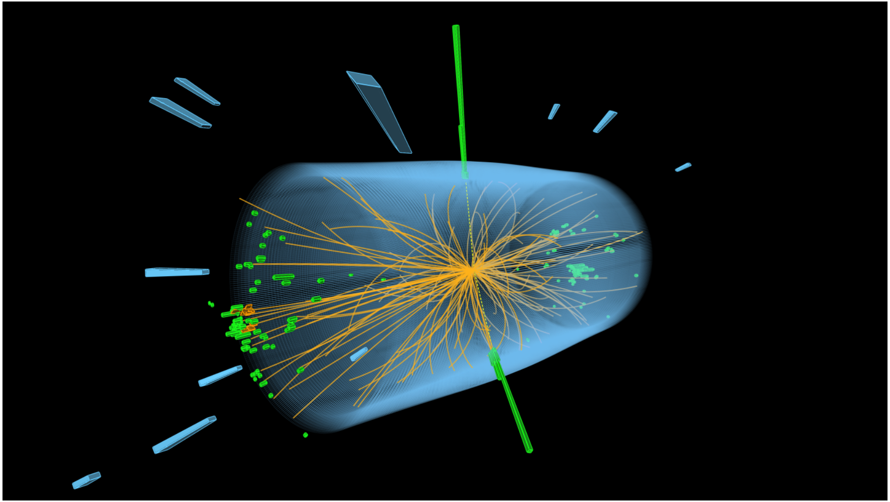
Higgs Discovery Timeline

- First serious Higgs searches at the LHC: **2011 dataset** (5 fb^{-1} @ 7 TeV)
- CERN public seminar (December 13, 2011)
  - **Excess** at $m_{\mathrm{H}} \approx 125\,\mathrm{GeV}$, **both** in ATLAS and CMS
  - $\approx 3\,\sigma$ ($\approx 2\,\sigma$) local (global) significance
- Update with 2011 data + first part of 2012 data (July 4, 2012):
  - Significance: $\mathbf{5.0\,\sigma/4.9\,\sigma}$ in ATLAS/CMS on $5 + 5\mathrm{fb}^{-1}$ per experiment
- CERN DG R. Heuer:

  "As a layman I would say: 'I think we have it!'"

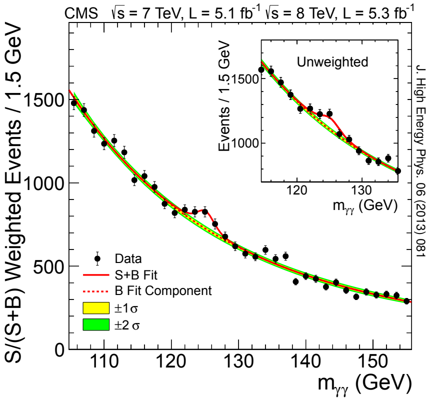
July 4th, 2012

H$\rightarrow \gamma\gamma$ Candidate



H $\rightarrow \gamma\gamma$ Analysis

- Signature: **small narrow peak** on huge **combinatorial** background



$H \to \gamma\gamma$ Analysis

Karlsruhe Institute of Technology

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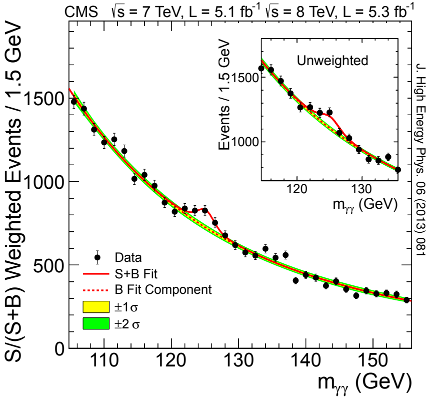
- Detect **photons** (ECAL) and e^+e^- pairs from **photon conversion** before ECAL



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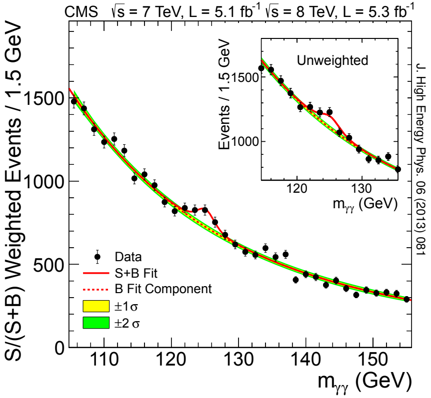
- **Dijet tag** for VBF Higgs production



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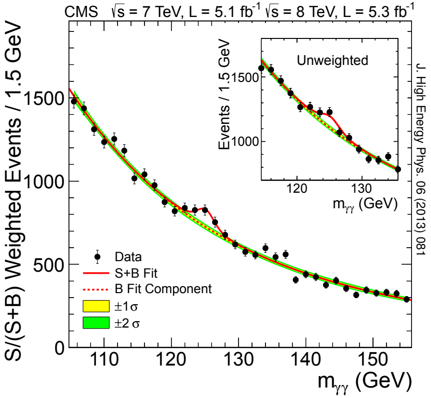
- Background: QCD **diphoton** production + **jets misidentified as photons**
- Background **estimated from data**: fit empirical function outside signal region



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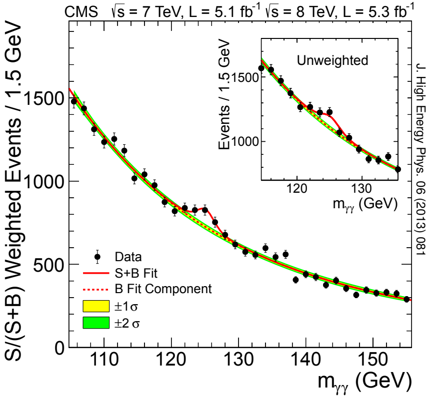

- Signal and background separation: **cut-based** or **boosted decision trees** (ECAL cluster shape, object kinematics, consistency with primary vertex)

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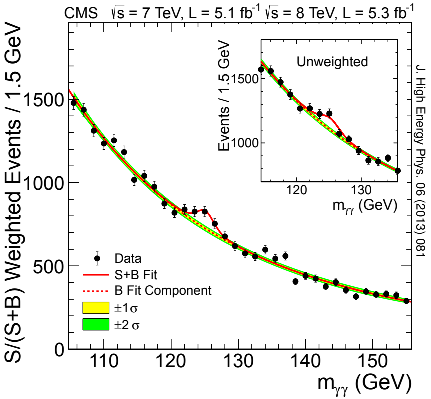
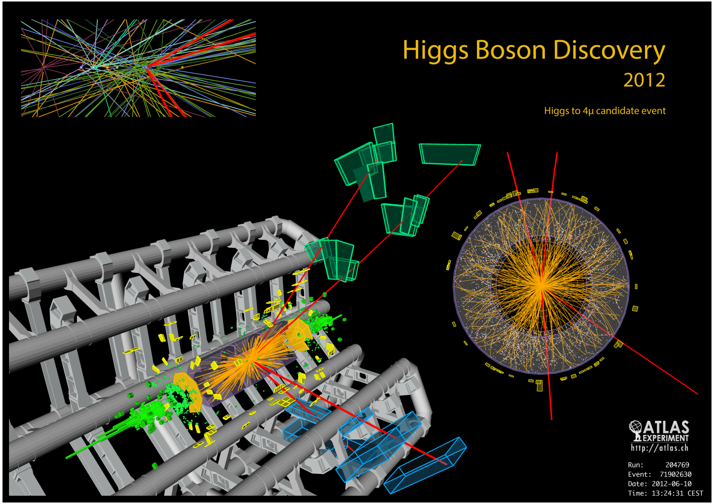


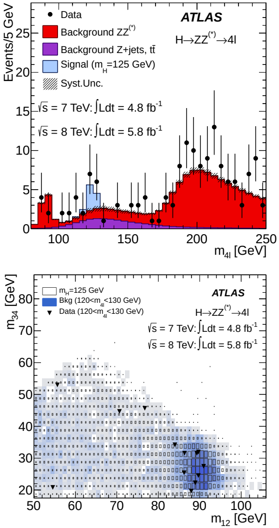
- Signal and background separation: **cut-based** or **boosted decision trees** (ECAL cluster shape, object kinematics, consistency with primary vertex)
- Experimental challenge: excellent calibration of **photon energy scale**

H→ZZ→ 4ℓ Candidate



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

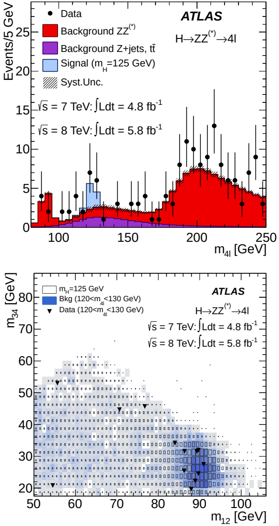
- Signature: **4 isolated high-p_T leptons** (e, μ), invariant mass of one pair compatible with Z boson



Phys.Lett. B716 (2012) 1

$H \to ZZ \to 4\ell$ Analysis

- Signature: **4 isolated high-p_T leptons** (e, μ), invariant mass of one pair compatible with Z boson
- Sensitive over **wide Higgs-boson mass range** (100–600 GeV)
- Excellent Higgs mass resolution **1–2 %**



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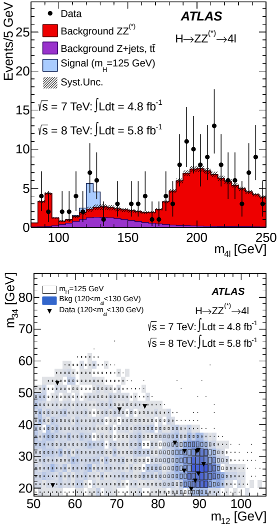
- Background:
  - **ZZ* continuum**: estimated from MC
  - Z $+$ jets, $t\bar{t}$: estimated from control regions in data



Phys.Lett. B716 (2012) 1

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- Background:
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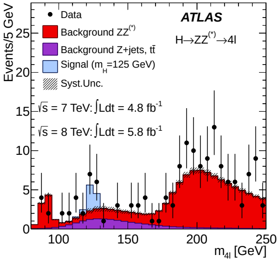
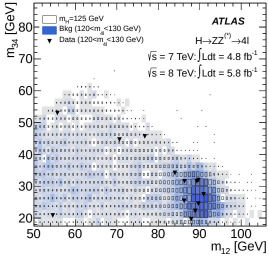
  - $Z +$ jets, $t\bar{t}$: estimated from control regions in data
- Selection: kinematics of 4-lepton system (5 angles, 2 pair masses)





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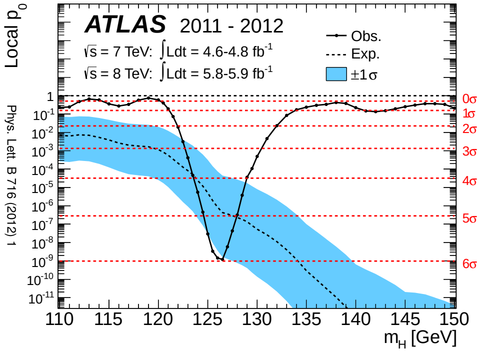
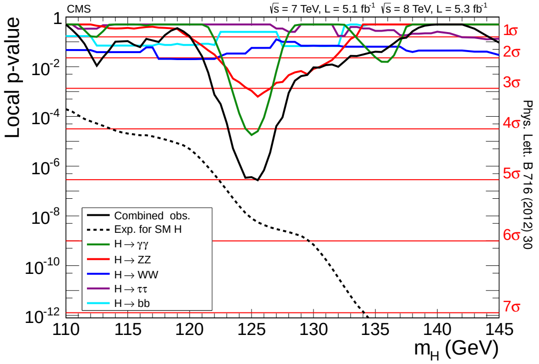
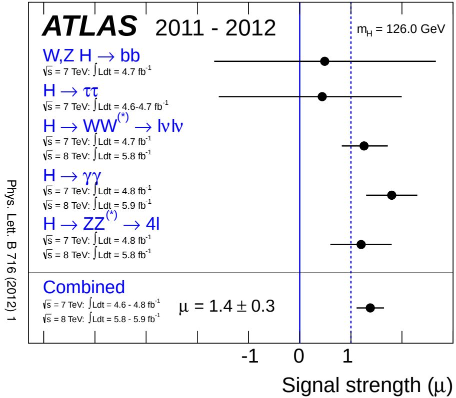
Combination of Decay Channels

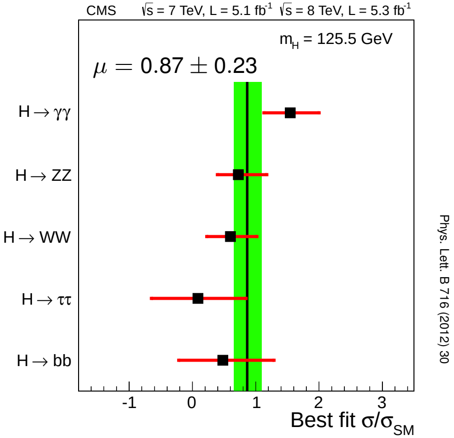




- Best sensitivity: **combination** of all decay channels **H** $\rightarrow \gamma\gamma$, **H** $\rightarrow$ **ZZ**$(^*) \rightarrow$ **4**ℓ, H $\rightarrow$ WW$(^*) \rightarrow \ell\nu\ell\nu$, H $\rightarrow \tau\tau$, H $\rightarrow$ b$\bar{\text{b}}$
- Local p values for combination: $\geq$ **5** $\boldsymbol{\sigma}$ **excess** around $m_{\text{H}} = 125\,\text{GeV}$

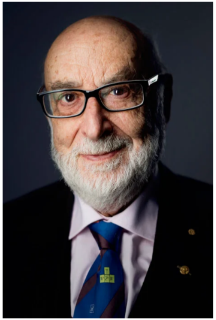
Best-Fit Signal Cross Section





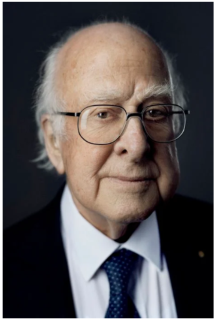
- All decay channels **compatible with SM** ($\mu = 1$)
- First measurement of m_H: 126.0 ± 0.6 GeV (**ATLAS**) 125.3 ± 0.6 GeV (**CMS**)

The Nobel Prize in Physics 2013



François Englert

Prize share: 1/2



Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "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"

Summary of Searches for the Higgs Boson

- Higgs searches at the **Tevatron**
  - Challenging: low cross sections, large backgrounds
  - Combination of all analysis channels in CDF and D0: **up to 3 σ excess** compatible with Higgs boson production in **115 GeV** $<$ m_H $<$ **140 GeV**
- Large **theory effort**: accurate predictions of Higgs signals and important backgrounds (up to NNNLO)
- July 4, 2012: **discovery** of a "Higgs-like particle" at the LHC
  - Main discovery channels: $H \to \gamma\gamma$, $H \to ZZ^{(*)} \to 4\ell$ (mass peaks)
  - Other channels contributing: $H \to WW^{(*)} \to \ell\nu\ell\nu$, $H \to \tau\tau$, $H \to b\bar{b}$
  - Combination of all analysis channels: $\geq$ **5 σ** independently in ATLAS and CMS

High-Resolution Channels: Now and Then

- Decay channels with **best resolution**:
  - $H \to \gamma\gamma$ (low signal purity)
  - $H \to ZZ \to 4\ell$ (small signal rate)

$\to$ typically **first choice for property measurements**

High-Resolution Channels: Now and Then

Karlsruhe Institute of Technology

- Decay channels with **best resolution**:
  - $H \to \gamma\gamma$ (low signal purity)
  - $H \to ZZ \to 4\ell$ (small signal rate)

$\to$ typically **first choice for property measurements**

- Experimental challenge: control of **calibration uncertainties**
  - $\gamma\gamma$: **ECAL response** and **material** in front of ECAL
  - 4ℓ: **energy/momentum scale** and resolution for e/μ

High-Resolution Channels: Now and Then

- Decay channels with **best resolution**:
  - $H \to \gamma\gamma$ (low signal purity)
  - $H \to ZZ \to 4\ell$ (small signal rate)

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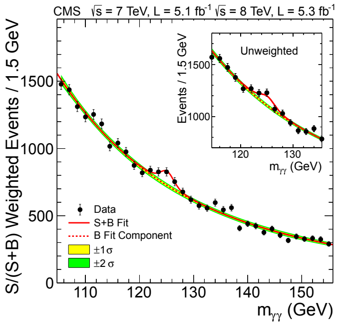
At discovery (part of Run 1 data)



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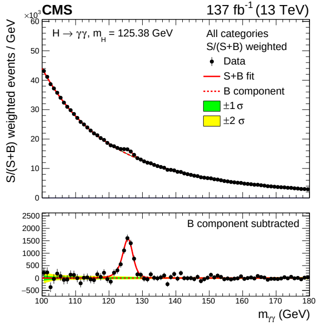
today (full Run 2 dataset)



JHEP 07 (2021) 027

High-Resolution Channels: Now and Then

- Decay channels with **best resolution**:
  - $H \to \gamma\gamma$ (low signal purity)
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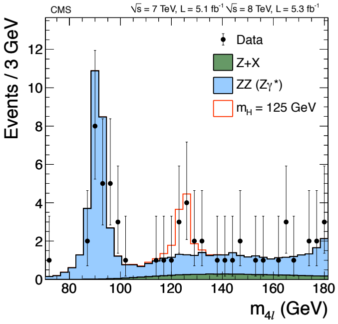
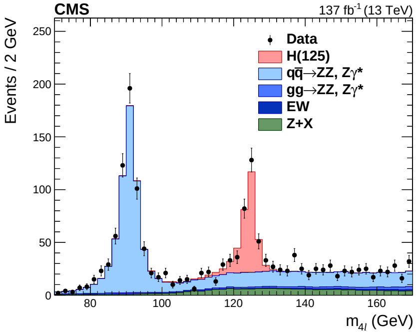


J. High Energy Phys. 06 (2013) 081

today (full Run 2 dataset)



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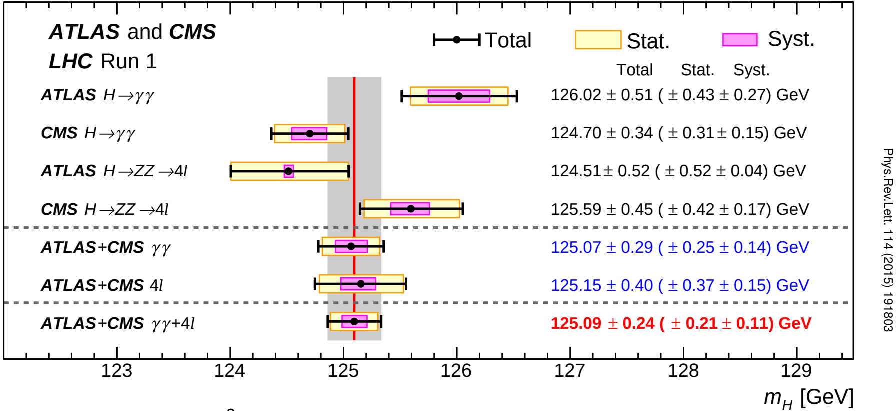
Higgs-Boson Mass m_H

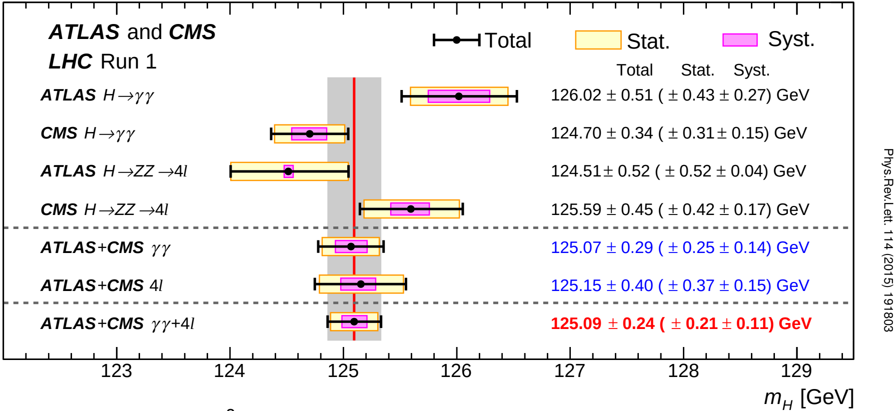
- Reminder: importance of the Higgs-boson mass
  - m_H **only free parameter of SM Higgs sector**: consistency check of SM (relation to m_t and m_W through quantum corrections)
  - Improved knowledge on m_H $\rightarrow$ more precise predictions of other Higgs properties
  - Decay channels with **best mass resolution**: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$

Higgs-Boson Mass m_H: Run 1 Combination



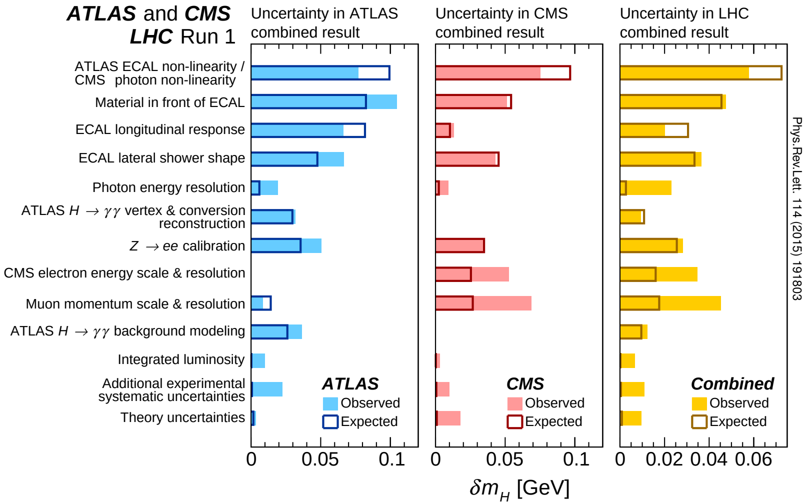
- Measurement precision: $2 \cdot 10^{-3}$ → one of **most precisely known** SM parameters, still **statistics limited**

Higgs-Boson Mass m_H: Run 1 Combination



- Measurement precision: $2 \cdot 10^{-3}$ $\rightarrow$ one of **most precisely known** SM parameters, still **statistics limited**
- Breakdown of systematic uncertainties: ± 0.11 (scale) $\pm\, 0.02$ (others) $\pm\, 0.01$ (theory) GeV
  $\rightarrow$ **energy scale** uncertainties dominant

Higgs-Boson Mass m_H: Uncertainties



Higgs-Boson Mass m_H: Combination

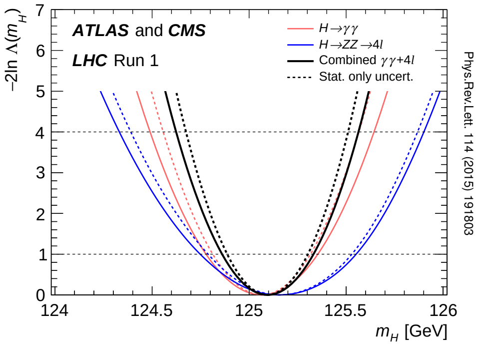
- Combination at level of **likelihoods**: minimise negative logartihm of **profile-likelihood ratio**

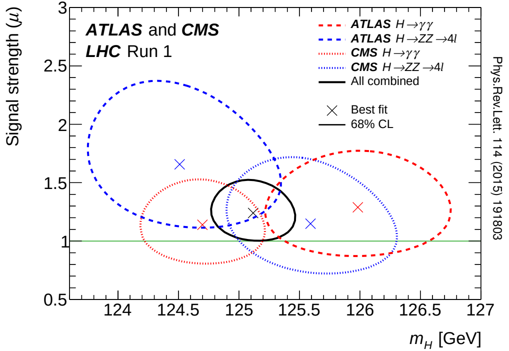
$$\Lambda(m_H) = \frac{\mathcal{L}(m_H, \hat{\hat{\theta}}(m_H))}{\mathcal{L}(\hat{m}_H, \hat{\theta})}$$

$\hat{m}_H, \hat{\theta}$: values that maximise $\mathcal{L}$ globally

$\hat{\hat{\theta}}(m_H)$: values that maximise $\mathcal{L}$ for given m_H

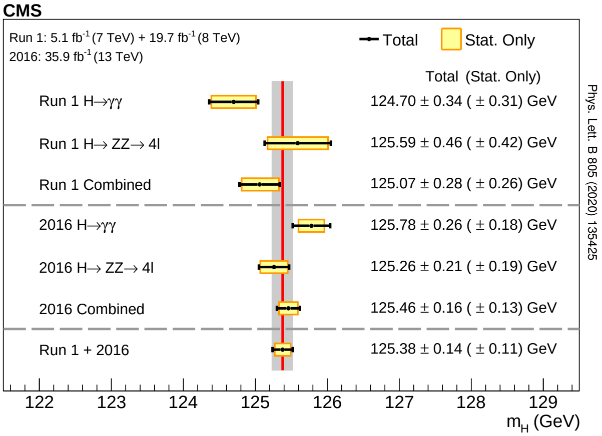
- Λ function of mass-dependent $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ signal strengths





Higgs-Boson Mass m_H: Status Summer 2023

- Most precise measurement in $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ decay channels by the CMS Collaboration
  - 3D fit of mass, event-by-event resolution, S/B discriminant
  - $m_H = 125.38 \pm 0.11\ (\text{stat}) \pm 0.08\ (\text{syst})\ \text{GeV}$
  - **Precision: $<$ 0.1 % level**



Summary

- Coupling structure of the Higgs boson well-defined
  - Coupling strength determined by the Higgs boson mass
  - But Higgs boson mass unknown from theory, many signatures to cover experimentally
- Long-lasting **search for the Higgs boson** at LEP, Tevatron and LHC
- Finally observed by ATLAS and CMS at the LHC in 2012
  - Main discovery channels: **H** $\rightarrow \gamma\gamma$, **H** $\rightarrow$ **ZZ**$(^*) \rightarrow$ **4**ℓ (mass peaks)
  - Other channels contributing: H $\rightarrow$ WW$(^*) \rightarrow l\nu l\nu$, H $\rightarrow \tau\tau$, H $\rightarrow$ b$\bar{\text{b}}$
- Measurements of Higgs boson properties become feasible with more data
- Higgs boson mass already known up to a level of 0.1 %