The Quest for the Origin of Mass: Status of Higgs Particle Searches

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Victoria, B.C., Canada
28 March 2001

Mass and the Standard Model of Particle Physics

- Higgs mechanism

Standard Model Higgs Searches

- LEP: status
- Tevatron: status and prospects
- LHC: prospects

Beyond the SM: Supersymmetry

Conclusions

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Abstract

The Standard Model (SM) of particle physics offers a very successful description of the interactions of the fundamental constituents of matter at the smallest scales and highest energies accessible to current experiments. In particular, the global analysis of electroweak observables yields superb agreement with the SM predictions. A key ingredient of the SM is the postulated existence of a self-interacting scalar field, the Higgs field, with a non-zero vacuum expectation value responsible for the spontaneous electroweak symmetry hiding and the generation of the W and Z mass. Within the SM, it is their interaction with the Higgs field that gives rise to the mass of quarks and charged leptons. An experimentally important by-product of the SM electroweak symmetry hiding mechanism is the existence of the Higgs particle.

The search for the Higgs is central to many particle physics efforts, and crucial to our understanding of the origin of mass.
After a review of the concept of mass and of the SM, the status of searches for the SM Higgs (LEP and Tevatron) and prospects for future discoveries (Tevatron and LHC) are summarized.

Mass and Newton

Sir Isaac Newton
1642-1727

The concept of mass lies at the heart of Newtonian physics

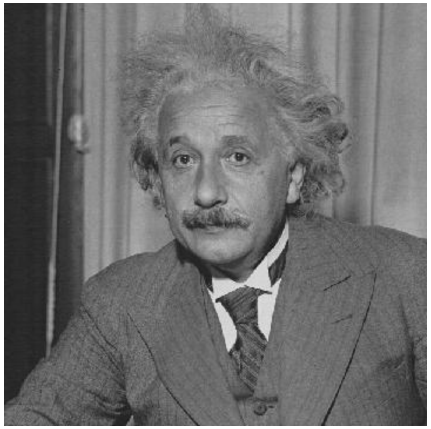
$F = ma$ $\longrightarrow$ **2nd Law**

$F = \frac{GMm}{r^2}$ $\longrightarrow$ **Law of Universal Gravitation**

Mass appears as a primary characteristic of any physical object

Mass and Einstein

$$\left.\begin{array}{l} E = \gamma m c^2 \\ p = \gamma m \mathrm{v} \end{array}\right\} \quad \begin{array}{l} E^2 = (pc)^2 + \left(mc^2\right)^2 \\ \dfrac{pc}{E} = \dfrac{\mathrm{v}}{c} \end{array} \qquad \gamma \equiv \left[1 - \left(\tfrac{\mathrm{v}}{c}\right)^2\right]^{-1/2}$$



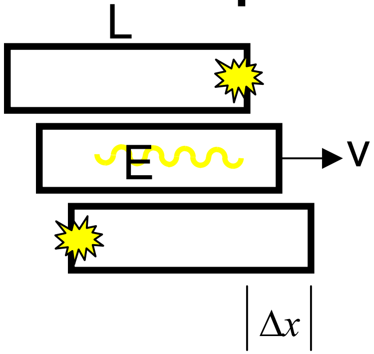
Albert Einstein
1879-1955

⇒ $m = 0 \quad \rightarrow \quad E = pc \quad \text{and} \quad \mathrm{v} = c$

massless particles carry momentum!!

⇒ $E = mc^2 \quad \rightarrow \quad m = \dfrac{E}{c^2}$

equivalence of mass and energy!!



$$M_{\text{box}}\mathrm{v} = \frac{E}{c}$$

$$\Delta x = \mathrm{v}\Delta t \approx L\frac{\mathrm{v}}{c}$$

Isolated system: $M_{\text{pulse}} L = M_{\text{box}} \Delta x$

⇒ $M_{\text{pulse}} c^2 = E$

Mass now appears less basic, not so irreducible

Mass and Einstein

Equivalence Principle: The response of a body to gravitation is independent of its mass

Newton → $a = \frac{GM}{r^2}$ independent of *m*!

Einstein → $$\underbrace{R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R} = \underbrace{\frac{8\pi G}{c^4} T^{\mu\nu}}$$

“palace of gold”
curvature of space-time

“hovel of wood”
energy-momentum of matter and radiation

↑

This is where masses of particles occur… raw

Can mass be replaced by something finer?

Mass and Quantum Mechanics

Radiation and Matter really are particulate

Their dynamics is given by a quantum theory where waves associated with the particles give us a measure of the probability of the state of the particles

de Broglie - Einstein → $E = h\nu$ $\quad p = \dfrac{h}{\lambda}$

The waves follow wave equations

Dirac equation → $e^{\pm}$

Maxwell equations → γ

What is waving??

One can learn about the structure of a crystal by studying e⁻ diffraction

$$\lambda = h/p = 1.23\,\mathring{A} \qquad \text{for} \quad K = 100\,\text{eV}$$

… even if the electrons are sent one at at time!!

Where is the mass of the electron?

Mass and Quantum Field Theory

The primary elements of reality are fields

Particles are quanta of excitations of fundamental fields

⟹ Particles acquire the properties of the field

- charge (global phase invariance)
- spin (field behavior under Lorentz transformation)
- mass

ALL electrons and positrons are quanta of excitations of ONE Dirac field

electrical charge $\pm e$, spin 1/2, same mass

What does the mass of a field mean?

From now on we use $\hbar = c = 1$

Gauge Invariance and the EM Interaction

Consider the interaction between the Dirac field and Maxwell field

Free Dirac field $\mathsf{L}_D = \overline{\psi}\left[i\gamma^\mu \partial_\mu - m\right]\psi \qquad \overline{\psi} \equiv \psi^\dagger \gamma^0$

invariant under global phase transformation $\psi \xrightarrow{\varepsilon} \psi' = e^{-i\varepsilon}\psi$

Free Maxwell field $\mathsf{L}_M = -\tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} \qquad F^{\mu\nu}(x) \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$

invariant under gauge transformation $A^\mu \to A'^\mu = A^\mu + \partial^\mu f \qquad \forall f(x)$

Impose Dirac field local phase, $U(1)_Q$ gauge, invariance to the theory

Obtain $\mathsf{L} = \overline{\psi}\left[i\gamma^\mu D_\mu - m\right]\psi - \tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} \qquad D_\mu = \partial_\mu + iqA_\mu$

invariant under the gauge transformations

$$\begin{cases} \psi \xrightarrow{\varepsilon(x)} \psi' = e^{-i\varepsilon(x)}\psi \\ A^\mu \xrightarrow{\varepsilon(x)} A'^\mu = A^\mu + \frac{1}{q}\partial^\mu \varepsilon \end{cases}$$

The interaction is obtain from

$$\mathsf{L} = \mathsf{L}_D + \mathsf{L}_M + \mathsf{L}_{\text{int}} \Longrightarrow \mathsf{L}_{\text{int}} = -q\overline{\psi}\gamma^\mu A_\mu \psi$$

The requirement of $U(1)_Q$ gauge invariance couples both fields …

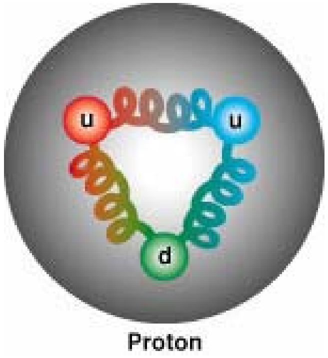
and prescribes the form of the interaction!! ⟹ QED

Most of the Mass

Quarks come in three colours

We require the strong colour interaction to be invariant under an $SU(3)_C$ gauge → QCD mediated by gluons

Gluons carry colour! → confinement



only colour singlets can exist freely

QCD with massless u and d quarks predicts the mass of the proton to about 10%!

$$m = E \quad \text{again!}$$

energy of gluons and quarks in baryons

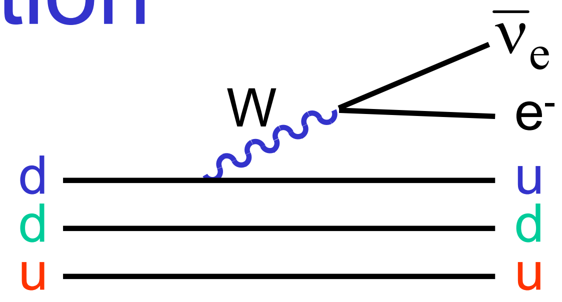
Protons and neutrons make up over 99% of the mass of ordinary matter...

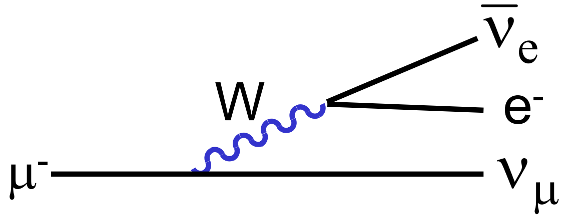
We are getting closer to "mass without mass"!

Weak Interaction

We want to obtain the weak interaction from a gauge principle

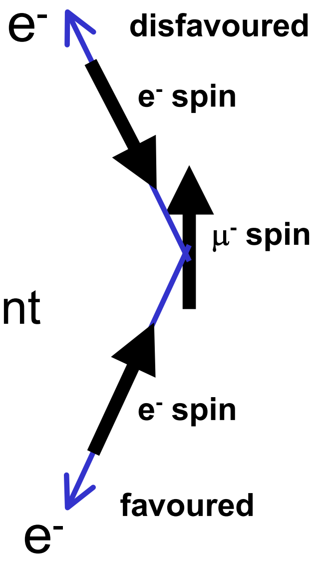
But the weak interaction is mediated by massive particles, and boson mass terms violate gauge invariance...





Furthermore, the weak interaction violates parity! Charged weak interaction is only felt by
chiral-left particles
chiral-right antiparticles
} negative chirality (eigenvalue of γ_5)

Experiment → maximal chirality violation



Massless particles → chirality = helicity is Lorentz invariant
Massive particles → chirality ≠ helicity spin flip!

↓ **handedness**

Chirality and mass are not friendly neighbours

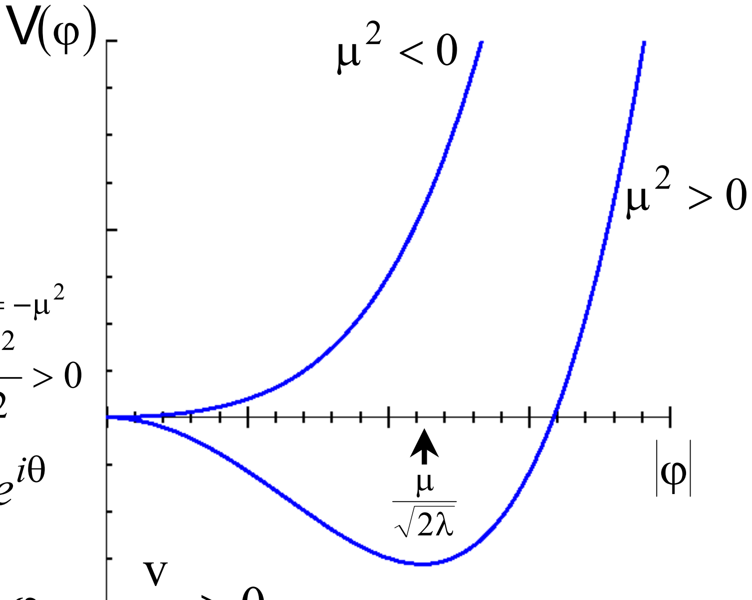
Chiral gauge invariance $SU(2)_L$ violated by ALL mass terms!

Goldstone Model

We want: gauge invariance to generate interactions
We need: gauge invariant mechanism to generate mass
→ hidden symmetry (spontaneous symmetry "breaking")

Consider a model where the equilibrium state is not unique
nature makes a choice, hiding the invariance of the theory
equilibrium state: all fields null, except one $\varphi(x) \neq 0$
Lorentz invariance → $\varphi(x)$ is a scalar

Goldstone model: consider



$$L = (\partial_\mu \varphi)^* (\partial^\mu \varphi) - V(\varphi)$$ $\varphi(x)$ is a complex scalar

$$V(\varphi) = -\mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2 \qquad \lambda > 0$$

$\mu^2 < 0 \longrightarrow$ **Self-interacting Klein-Gordon field where** $m^2 = -\mu^2$

$\mu^2 > 0 \longrightarrow V(\varphi)\big|_{\min} = -\frac{\mu^2 v^2}{4} \Rightarrow |\varphi|^2 = |\varphi_0|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} > 0$

The equilibrium is characterized by $\varphi_0 = \frac{v}{\sqrt{2}} e^{i\theta}$

Nature spontaneously chooses, say, $\theta = 0 \rightarrow \varphi_0 = \frac{v}{\sqrt{2}} > 0$
always possible because of global U(1) phase invariance

Goldstone Model (continued)

We write $\varphi(x) = \frac{1}{\sqrt{2}}\left[\mathrm{v} + \sigma(x) + i\eta(x)\right]$ where $\sigma(x)$ and $\eta(x)$ measure the deviation of $\varphi(x)$ from equilibrium. We get

$$L = \tfrac{1}{2}(\partial_\mu \sigma)(\partial^\mu \sigma) - \mu^2 \sigma^2 + \tfrac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) + L_{\text{int}}$$

$$L_{\text{int}} = -\lambda \mathrm{v} \sigma\left(\sigma^2 + \eta^2\right) - \tfrac{1}{4}\lambda\left(\sigma^2 + \eta^2\right)^2$$

We can interpret →

$\sigma \to$ real Klein - Gordon field $\frac{1}{2} m^2 = \mu^2$

$\eta \to$ real Klein - Gordon field $m_\eta = 0$ → Goldstone boson field

and n.d.f do add up →

			n.d.f
Initially:	complex φ	→	2
After :	real massive σ	→	1
	real massless η	→	1

No truly massless Goldstone bosons are observed in nature

π^0, π^+, π^- come pretty close...

We need a hidden symmetry mechanism that does not generate physical massless Goldstone bosons

Higgs Model (Peter W. Higgs, 1929 -)

Generalize the Goldstone model to be invariant under U(1) gauge transformation $\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu$

Obtain $\mathrm{L} = \left(D_\mu \varphi\right)^* \left(D^\mu \varphi\right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \mathrm{V}(\varphi)$ $\quad \mathrm{V}(\varphi) = -\mu^2 \varphi^* \varphi + \lambda\left(\varphi^* \varphi\right)^2 \quad \lambda > 0$

Invariant under $\varphi \xrightarrow{\varepsilon(x)} \varphi' = e^{-i\varepsilon(x)} \varphi$

$$A^\mu \xrightarrow{\varepsilon(x)} A'^\mu = A^\mu + \frac{1}{q} \partial^\mu \varepsilon$$

$\mu^2 < 0$ ⟹ **Scalar electrodynamics with self-interacting Klein-Gordon field where** $m^2 = -\mu^2$

$\mu^2 > 0$ ⟹ $\mathrm{V}(\varphi)\big|_{\min} = -\dfrac{\mu^2 \mathrm{v}^2}{4} \Rightarrow |\varphi|^2 = |\varphi_0|^2 = \dfrac{\mu^2}{2\lambda} \equiv \dfrac{\mathrm{v}^2}{2} > 0$

The equilibrium is characterized by $\varphi_0 = \dfrac{\mathrm{v}}{\sqrt{2}} e^{i\theta}$

Nature spontaneously chooses, say, $\theta = 0 \to \varphi_0 = \dfrac{\mathrm{v}}{\sqrt{2}} > 0$

always possible because of global U(1) phase invariance

again, use $\varphi(x) = \frac{1}{\sqrt{2}}\left[\mathrm{v} + \sigma(x) + i\eta(x)\right]$

Higgs Model (continued)

Obtain

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu \sigma)(\partial^\mu \sigma) - \mu^2\sigma^2 + \tfrac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \tfrac{1}{2}(q\mathrm{v})^2 A^\mu A_\mu + q\mathrm{v}(\partial_\mu \eta)A^\mu + \mathcal{L}'_{\mathrm{int}}$$

can interpret $\sigma \to$ real Klein - Gordon field $\tfrac{1}{2}m^2 = \mu^2$

but cannot interpret $\eta \to$ real Klein - Gordon field $m_\eta = 0$

$A^\mu \to$ real Proca field $M_A = q\mathrm{v}$

aaarg!

and n.d.f would NOT add up

n.d.f

$$\text{Initially:} \begin{cases} \text{complex } \varphi & \to 2 \\ \text{real massless } A^\mu & \to 2 \end{cases} \to 4$$

!

$$\text{After :} \begin{cases} \text{real massive } \sigma & \to 1 \\ \text{real massless } \eta & \to 1 \\ \text{real massive } A^\mu & \to 3 \end{cases} \to 5$$

L contains an unphysical field which can be eliminated through a gauge transformation yielding the form

$$\varphi(x) = \tfrac{1}{\sqrt{2}}[\mathrm{v} + \sigma(x)]$$ unitary gauge

$\eta(x)$ ⟶ would-be Goldstone boson field

Higgs Model (end)

In this gauge, we obtain

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu \sigma)(\partial^\mu \sigma) - \mu^2 \sigma^2 - \tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} + \tfrac{1}{2}(qv)^2 A^\mu A_\mu + \mathcal{L}_{\text{int}}$$

$$\mathcal{L}_{\text{int}} = -\lambda v \sigma^3 - \tfrac{1}{4}\lambda \sigma^4 + \tfrac{1}{2} q^2 A^\mu A_\mu \left(2v\sigma + \sigma^2\right)$$

can interpret

$\sigma \rightarrow$ real Klein - Gordon field $\quad \tfrac{1}{2} m^2 = \mu^2$

$A^\mu \rightarrow$ real Proca field $\quad M_A = qv$

and n.d.f do add up →

$$\begin{array}{lll} & & \text{n.d.f} \\ \text{Initially:} & \left\{ \begin{array}{ll} \text{complex } \varphi & \rightarrow 2 \\ \text{real massless } A^\mu & \rightarrow 2 \end{array} \right\} & \rightarrow 4 \\ \text{After :} & \left\{ \begin{array}{ll} \text{real massive } \sigma & \rightarrow 1 \\ \text{real massive } A^\mu & \rightarrow 3 \end{array} \right\} & \rightarrow 4 \end{array}$$

The massless Goldstone boson field $\eta(x)$ has disappeared from the theory and has allowed the $A^\mu(x)$ field to acquire mass!! →

$\sigma(x)$ is a Higgs boson field

vector boson acquires mass without spoiling gauge invariance

→ **Higgs mechanism**

...and we get a prescription for the interactions between σ and A^μ!

Higgs Mechanism

A room full of physicists chattering quietly is like space filled with the Higgs field...

… a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step...

…this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...

…if a rumor crosses the room...

…it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles

ATLAS educational web page, adapted from an idea from Dr D. J. Miller

The Standard Model

of Electroweak and Strong Interactions

Gauge invariance
$U(1)_Y \times SU(2)_L \times SU(3)_C$


Glashow
1932-


Salam
1926-


Weinberg
1933-

Spontaneous symmetry hiding in the electroweak sector

Higgs mechanism: $U(1)_Y \times SU(2)_L \rightarrow U(1)_Q$

Residual (non-hidden) symmetry: $U(1)_Q \times SU(3)_C$

massless photons

massless gluons

The Standard Model

particle content

fermions (matter)

leptons $\begin{pmatrix}\nu_e \\ e\end{pmatrix} \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix} \quad \begin{matrix}0 \\ -1\end{matrix}$

quarks $\begin{pmatrix}u \\ d\end{pmatrix} \begin{pmatrix}c \\ s\end{pmatrix} \begin{pmatrix}t \\ b\end{pmatrix} \quad \begin{matrix}+2/3 \\ -1/3\end{matrix}$

matter

bosons

$U(1)_Y$ B

$SU(2)_L$ W_1, W_2, W_3

$\xrightarrow{\cancel{EW}}$ γ, W^+, W^-, Z^0 electro-weak

$SU(3)_C$ g_{1-8} → g_{1-8} strong

radiation

Higgs doublet $\varphi_1 + i\varphi_2$, $\varphi_3 + i\varphi_4$ → H^0

SM Higgs Interactions

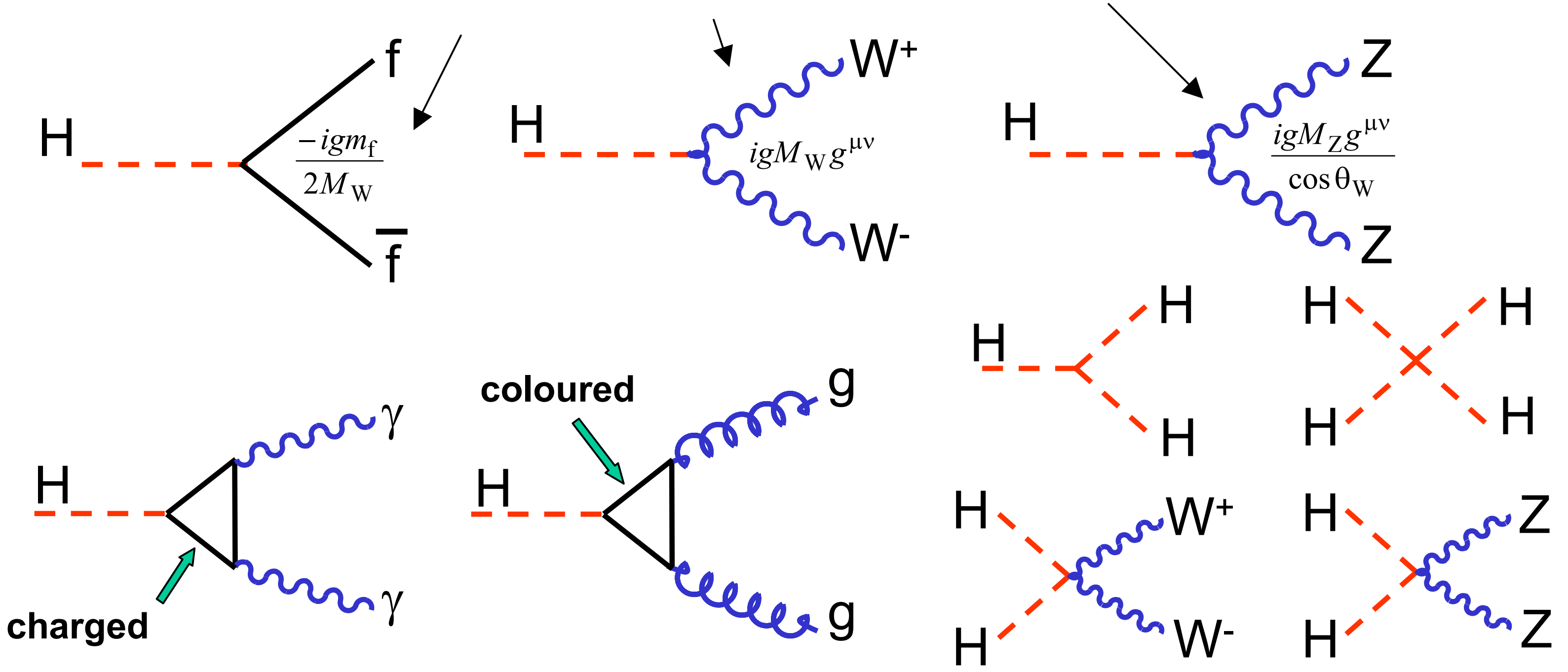
SM ⟶ Higgs mechanism with $U(1)_Y \times SU(2)_L$ gauge

$\varphi(x)$ is a complex doublet ⟶ W^+, W^-, Z acquire mass
left with one massive Higgs boson

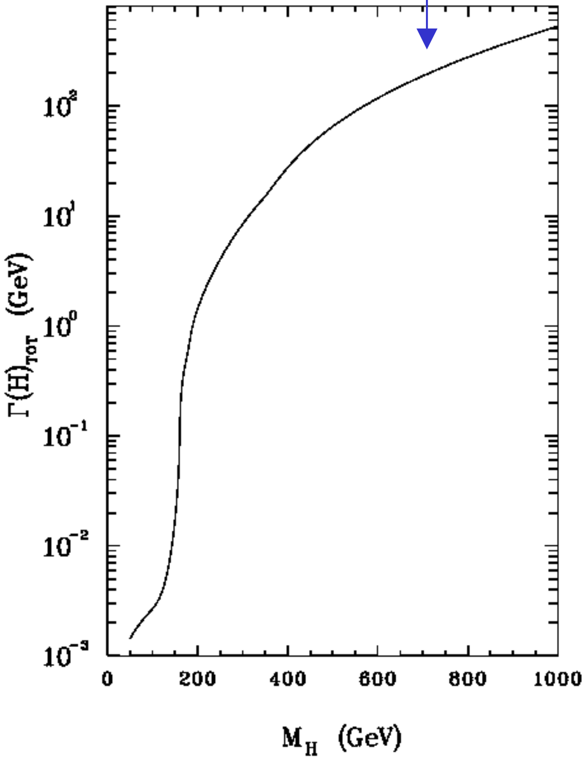
$$v = \left(\sqrt{2}G_F\right)^{-1/2} = 246\ \text{GeV}$$

$\varphi(x)$ coupling with massless fermion fields ⟶ fermion masses

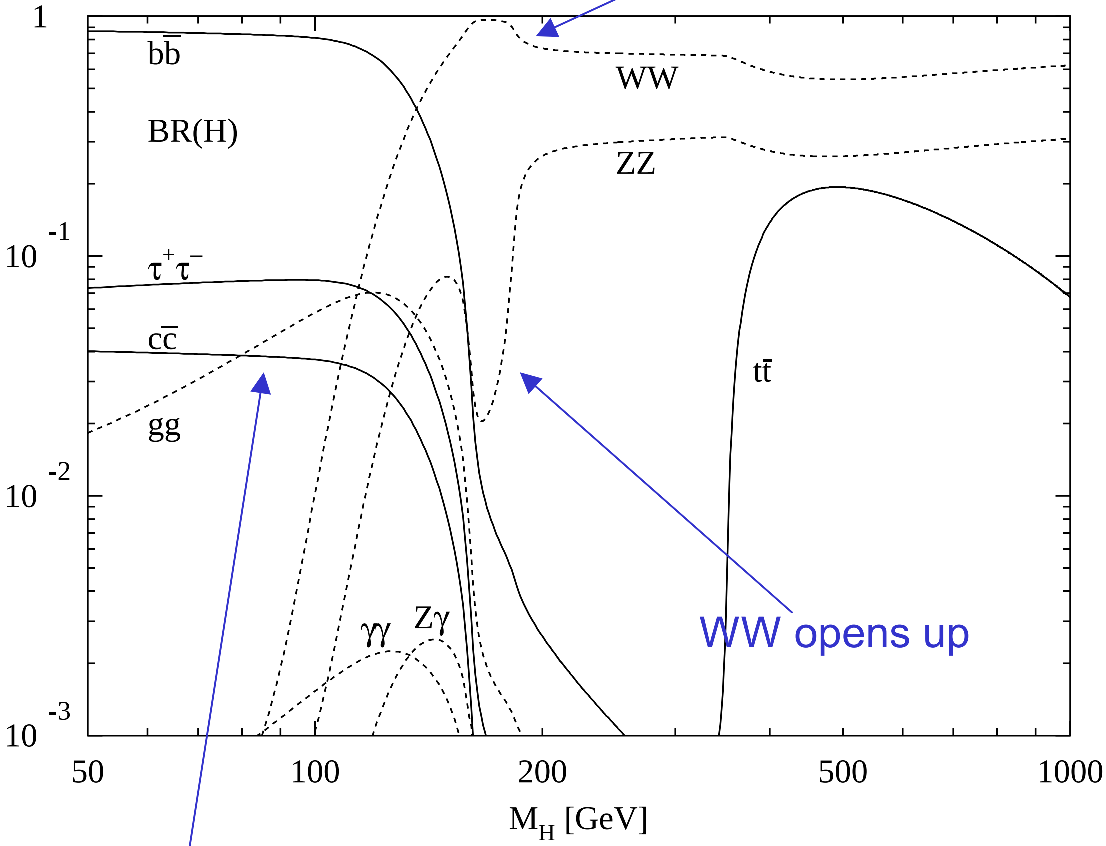
Higgs couplings proportional to mass $g^2 = 4\sqrt{2}G_F M_W^2$



SM Higgs Decays



Fat!



ZZ opens up

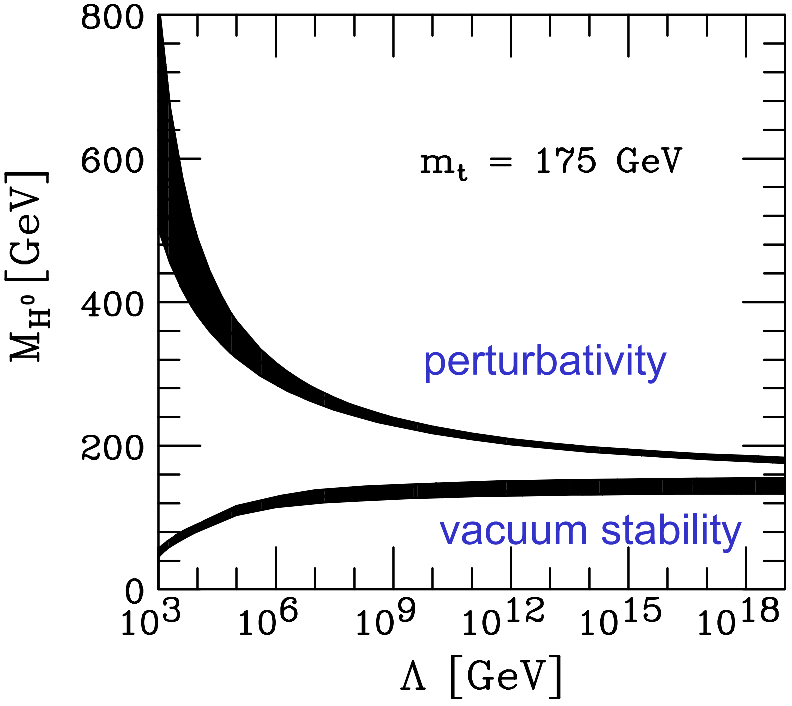
WW opens up

due to c reduced running mass

Theoretical Constraints on M_H

M_H is a free parameter of SM

but it must lie in a limited region for electroweak symmetry hiding to work

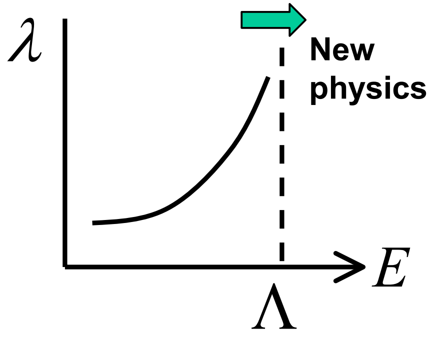


$130\text{ GeV} \approx< M_H \approx< 180\text{ GeV}$

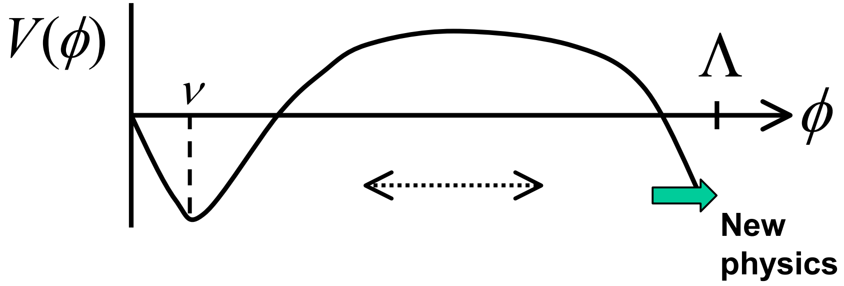
then, in principle consistent with $\Lambda = M_{PL}$

M_H is too large: the higgs self-coupling blows up at some scale Λ

$$m_H^2 = 2\lambda(m_H)v^2$$

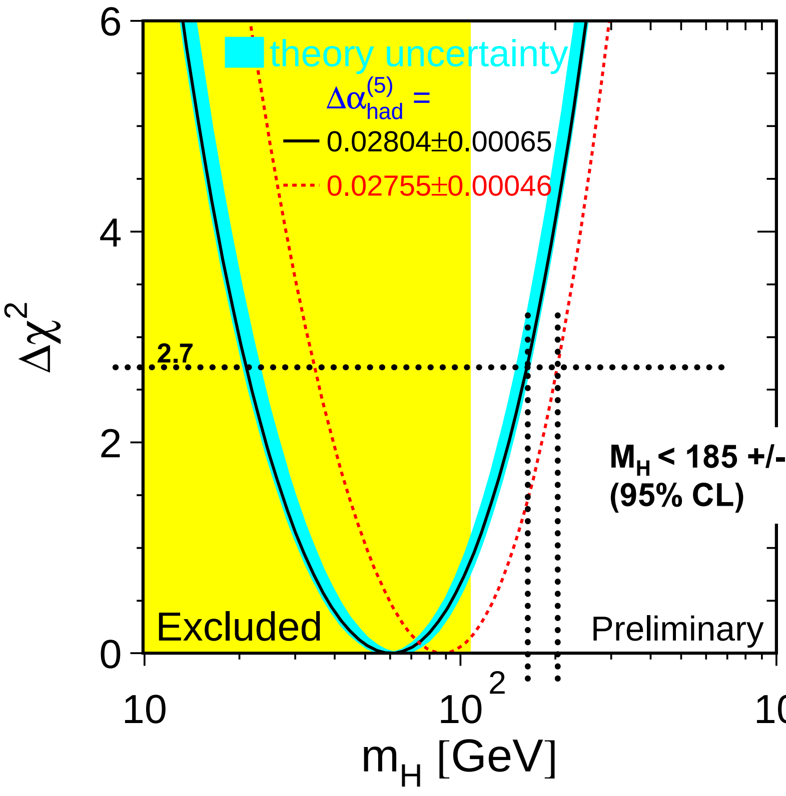


M_H is too small: the higgs potential develops a second (global!) minimum values of the scalar field of the order of Λ



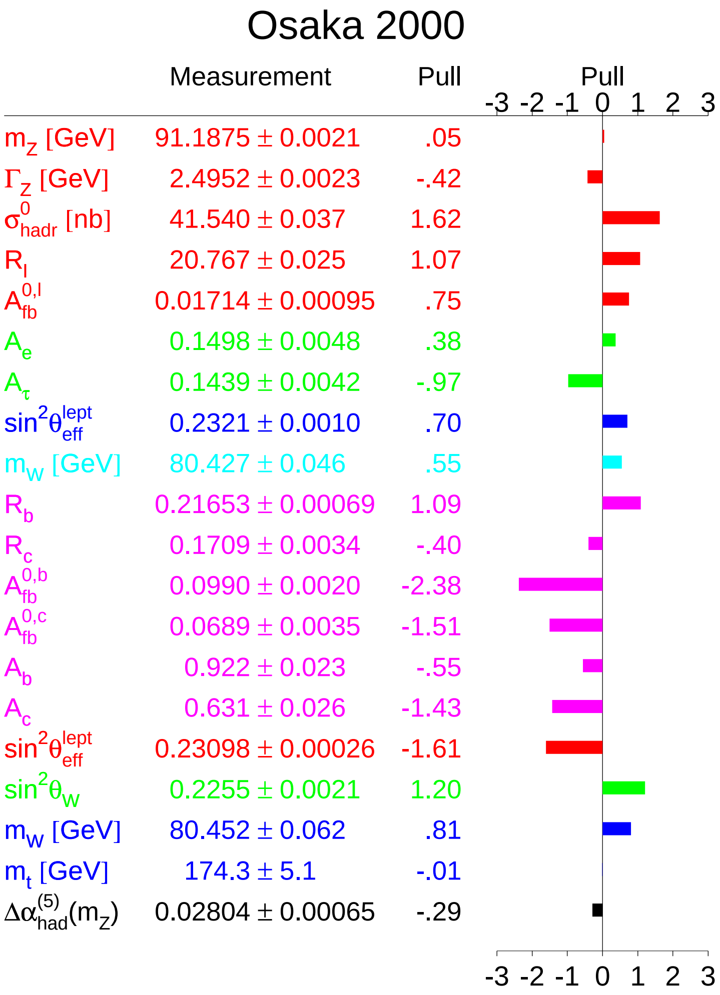
Experimental Constraints on M_H

H enters into loops… Global fits to precision EW data where M_H is the only unconstrained parameter



M_H < 185 +/- 20 GeV (95% CL)

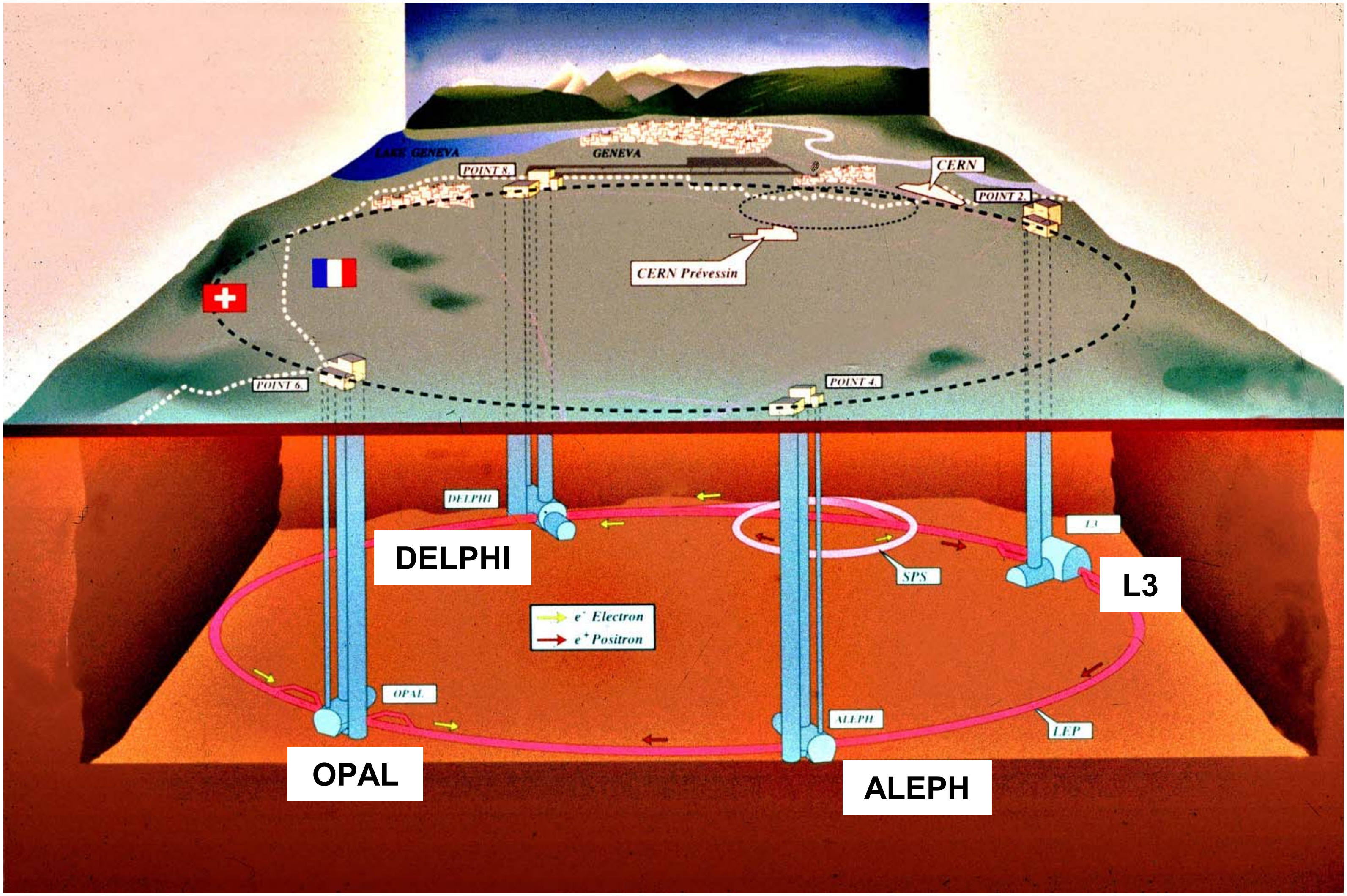
K. Graham UVic



Osaka 2000

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29

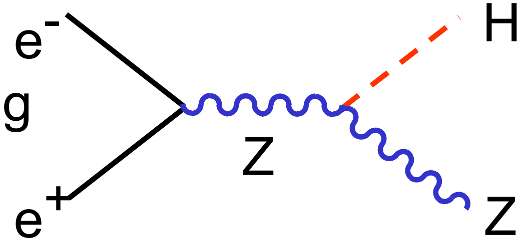
Large Electron Positron Collider



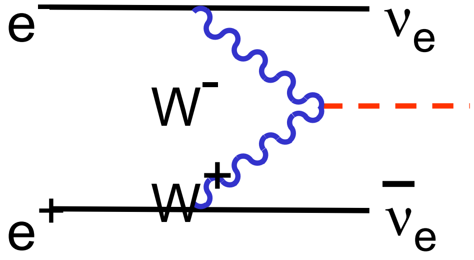
LEP Data Sets and SM Higgs Production

Stage	$\sqrt{s}$	Year	Luminosity
LEP 1	$\approx M_{Z^0}$	1989-1995	175 pb^{-1}
LEP 1.5	130-140 GeV	1995	5 pb^{-1}
LEP 2	161 GeV	1996	10 pb^{-1}
	172 GeV	1996	10 pb^{-1}
	183 GeV	1997	55 pb^{-1}
	189 GeV	1998	180 pb^{-1}
	192–202 GeV	1999	230 pb^{-1}
	200–209! GeV	2000	220 pb^{-1}

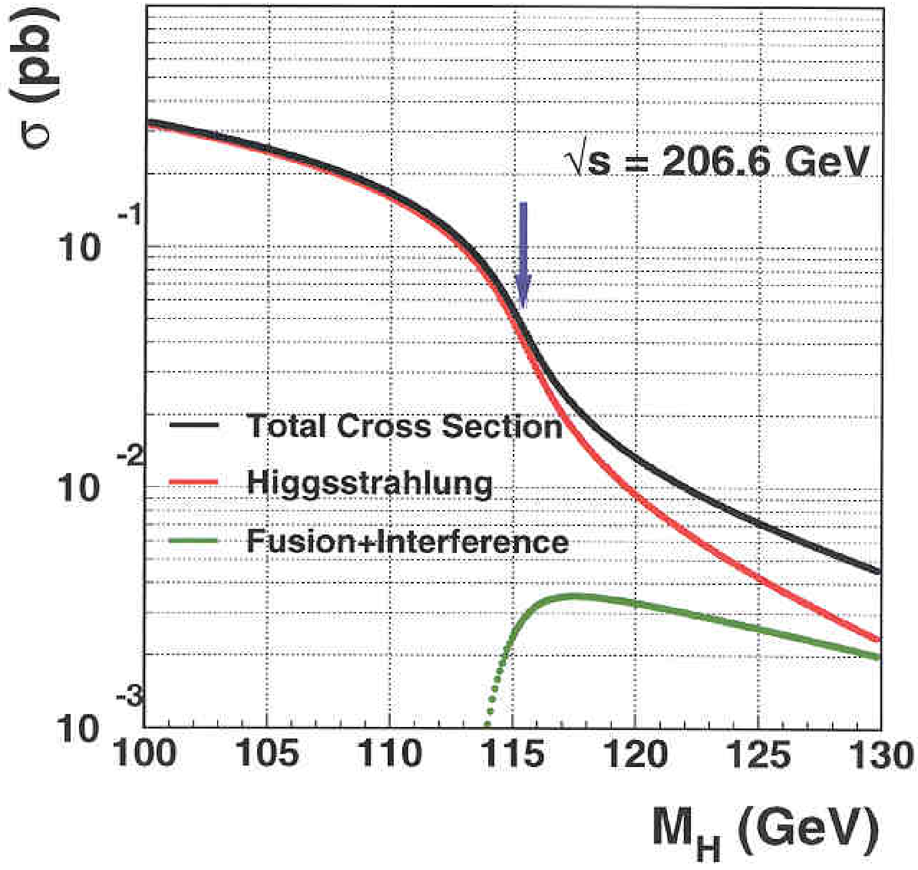
Higgsstrahlung



Fusion

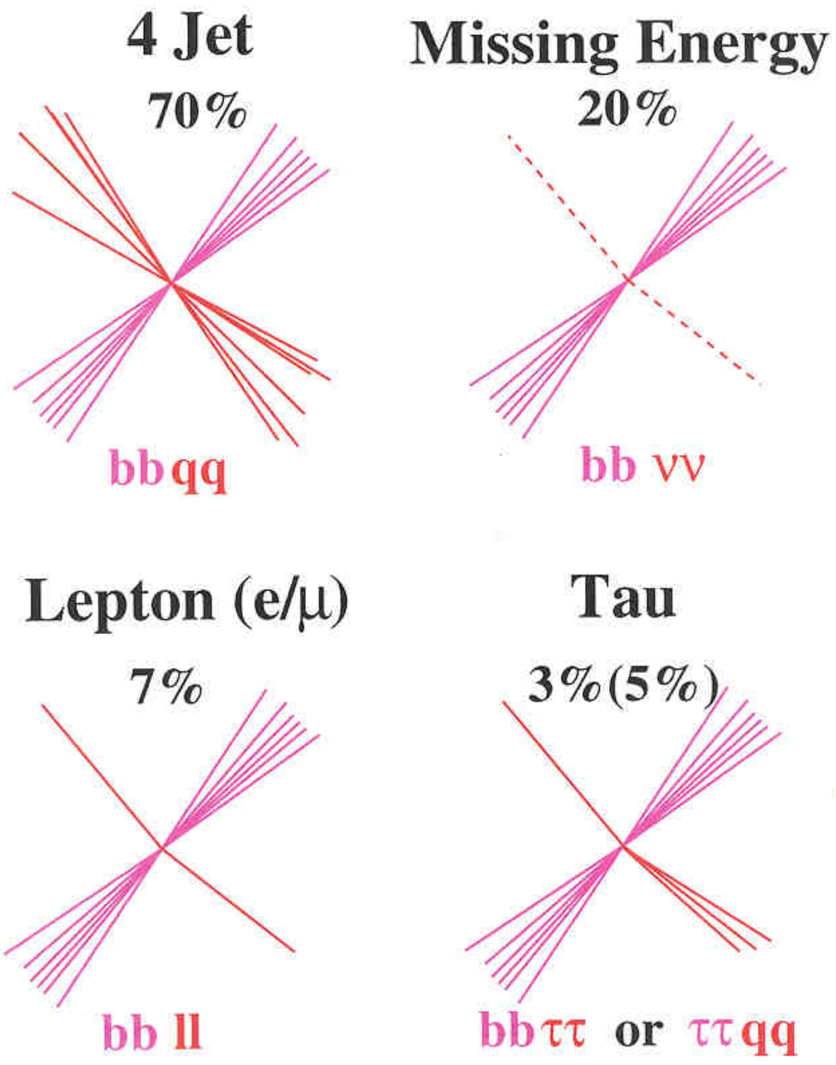


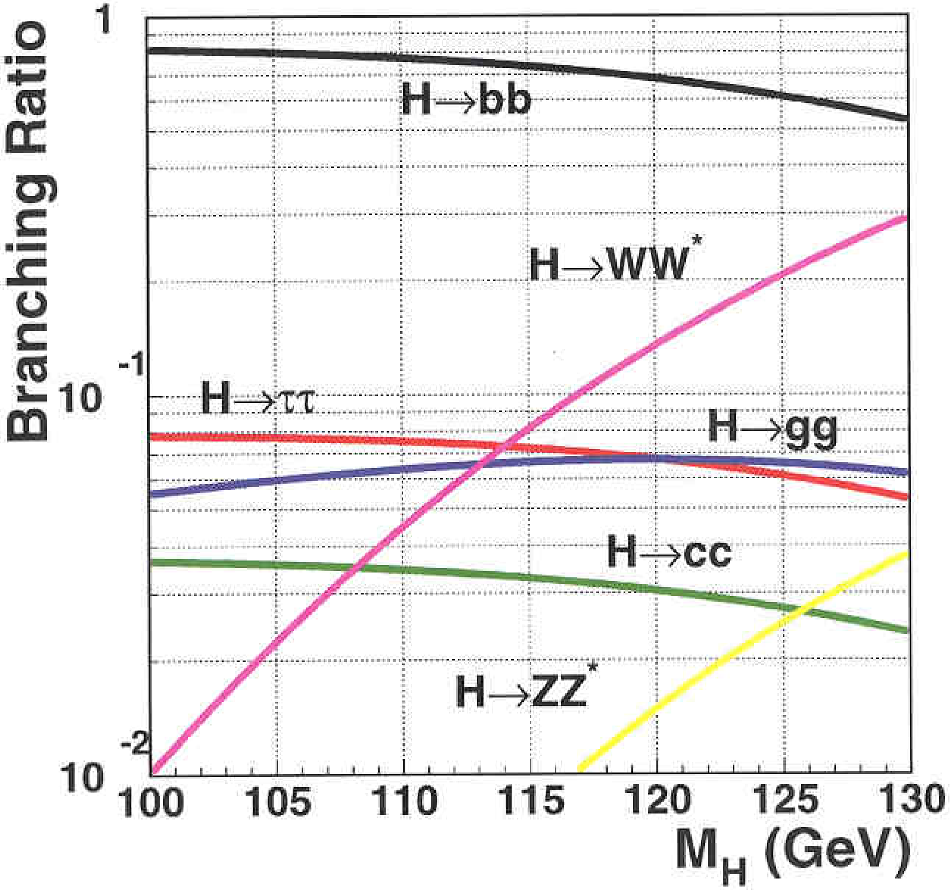
Rob McPherson



SM Higgs Topologies

Rob McPherson





LEP Higgs Candidates

LEP Higgs working group, 03/11/2000

ALEPH

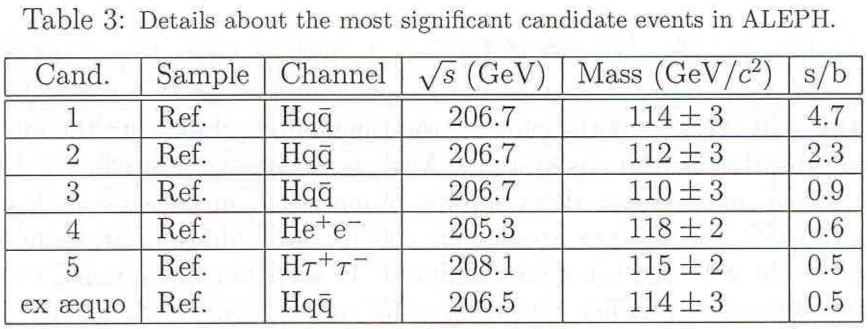


Table 3: Details about the most significant candidate events in ALEPH.

Cand.	Sample	Channel	$\sqrt{s}$ (GeV)	Mass (GeV/c^2)	s/b
1	Ref.	$Hq\bar{q}$	206.7	114 ± 3	4.7
2	Ref.	$Hq\bar{q}$	206.7	112 ± 3	2.3
3	Ref.	$Hq\bar{q}$	206.7	110 ± 3	0.9
4	Ref.	He^+e^-	205.3	118 ± 2	0.6
5	Ref.	$H\tau^+\tau^-$	208.1	115 ± 2	0.5
ex æquo	Ref.	$Hq\bar{q}$	206.5	114 ± 3	0.5

L3

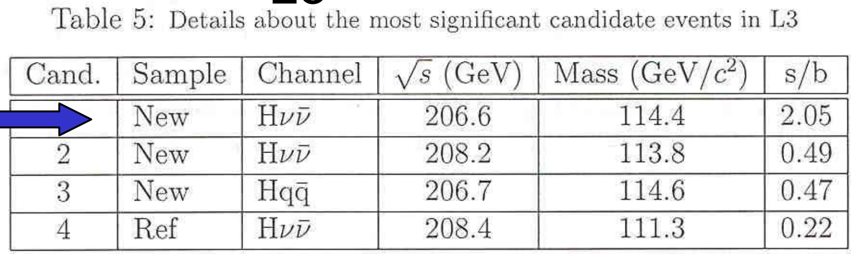


Table 5: Details about the most significant candidate events in L3

Cand.	Sample	Channel	$\sqrt{s}$ (GeV)	Mass (GeV/c^2)	s/b
	New	$H\nu\bar{\nu}$	206.6	114.4	2.05
2	New	$H\nu\bar{\nu}$	208.2	113.8	0.49
3	New	$Hq\bar{q}$	206.7	114.6	0.47
4	Ref	$H\nu\bar{\nu}$	208.4	111.3	0.22

DELPHI

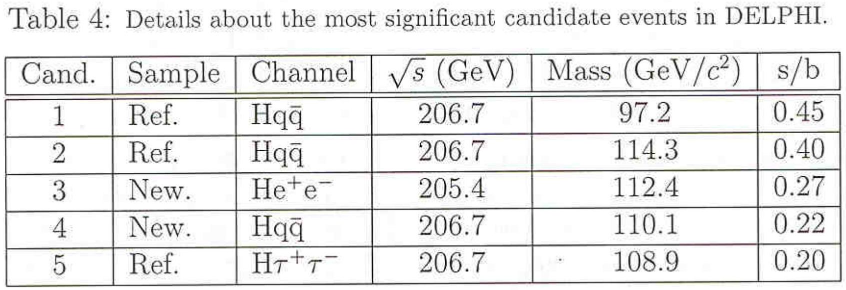


Table 4: Details about the most significant candidate events in DELPHI.

Cand.	Sample	Channel	$\sqrt{s}$ (GeV)	Mass (GeV/c^2)	s/b
1	Ref.	$Hq\bar{q}$	206.7	97.2	0.45
2	Ref.	$Hq\bar{q}$	206.7	114.3	0.40
3	New.	He^+e^-	205.4	112.4	0.27
4	New.	$Hq\bar{q}$	206.7	110.1	0.22
5	Ref.	$H\tau^+\tau^-$	206.7	108.9	0.20

OPAL

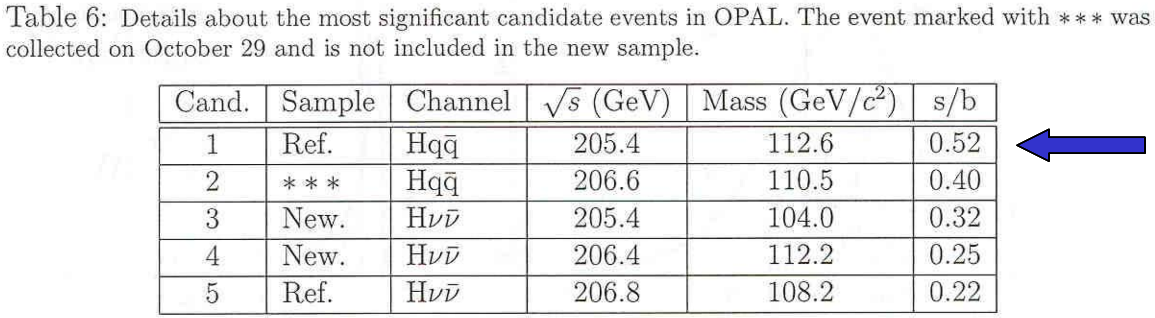
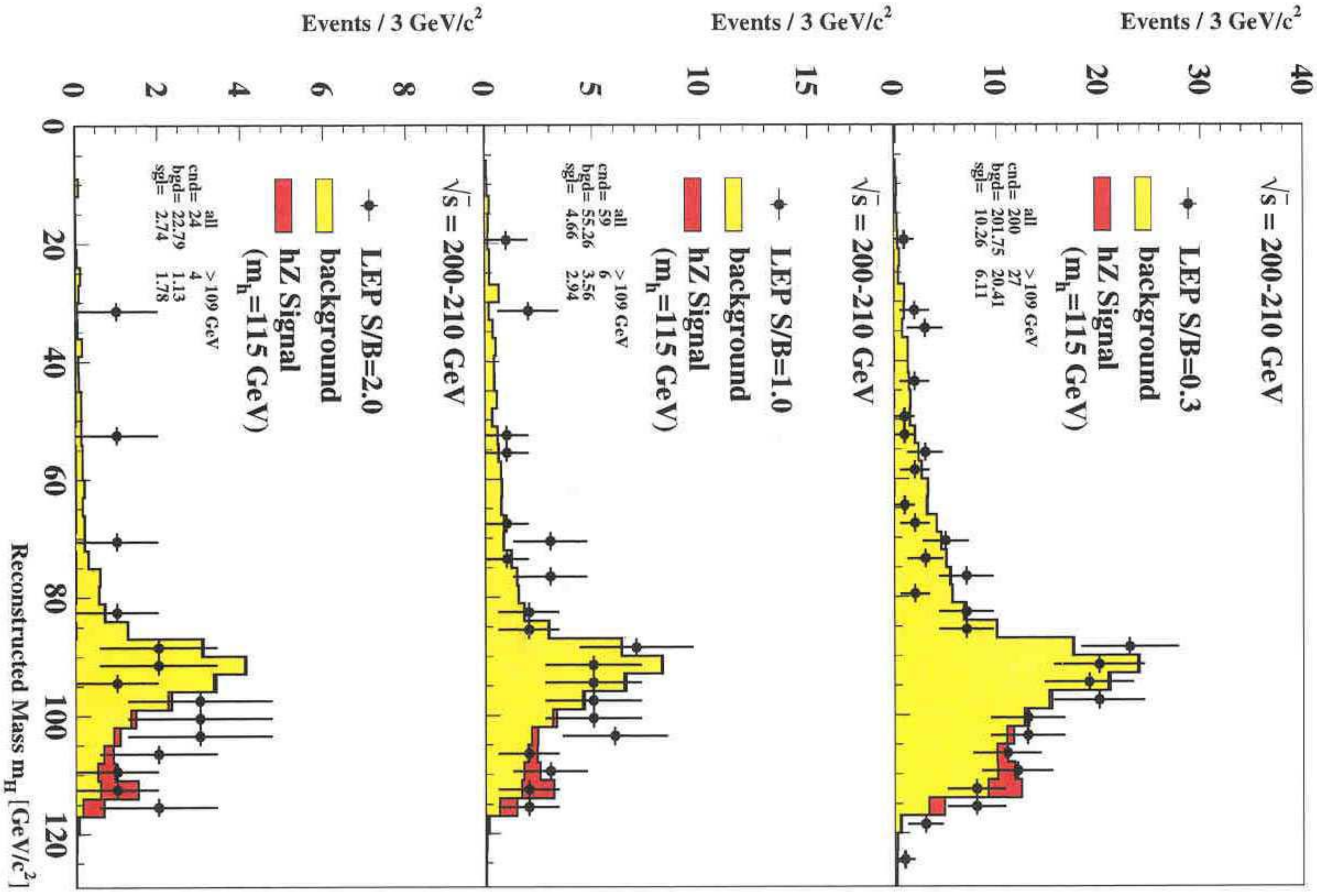


Table 6: Details about the most significant candidate events in OPAL. The event marked with $***$ was collected on October 29 and is not included in the new sample.

Cand.	Sample	Channel	$\sqrt{s}$ (GeV)	Mass (GeV/c^2)	s/b
1	Ref.	$Hq\bar{q}$	205.4	112.6	0.52
2	$***$	$Hq\bar{q}$	206.6	110.5	0.40
3	New.	$H\nu\bar{\nu}$	205.4	104.0	0.32
4	New.	$H\nu\bar{\nu}$	206.4	112.2	0.25
5	Ref.	$H\nu\bar{\nu}$	206.8	108.2	0.22

LEP Reconstructed Higgs Mass Spectra

M_H^{rec} with increasingly tighter selection criteria



high purity medium purity low purity

. . . not the whole story

Combining LEP SM Higgs Searches

4 decay modes
4 detectors
many $\sqrt{s}$

order of 100 "channels" with different sensitivities

$M_{\mathrm{H}}^{\mathrm{rec}}$ Reconstructed Higgs mass

G Global discrimination variable
(b-tag, kinematics, jet properties)

for each event in each channel

MC signal	$s_i\left(M_{\mathrm{H}}^{\mathrm{true}}\right)$
MC backgroung	b_i
Data	N_i

i is a bin in $\left(M_{\mathrm{H}}^{\mathrm{rec}}, G\right)$ space for each channel

Likelihood

$$\mathrm{L}(x) = \prod_i \frac{\exp(-x_i)\, x_i^{N_i}}{N_i!}$$

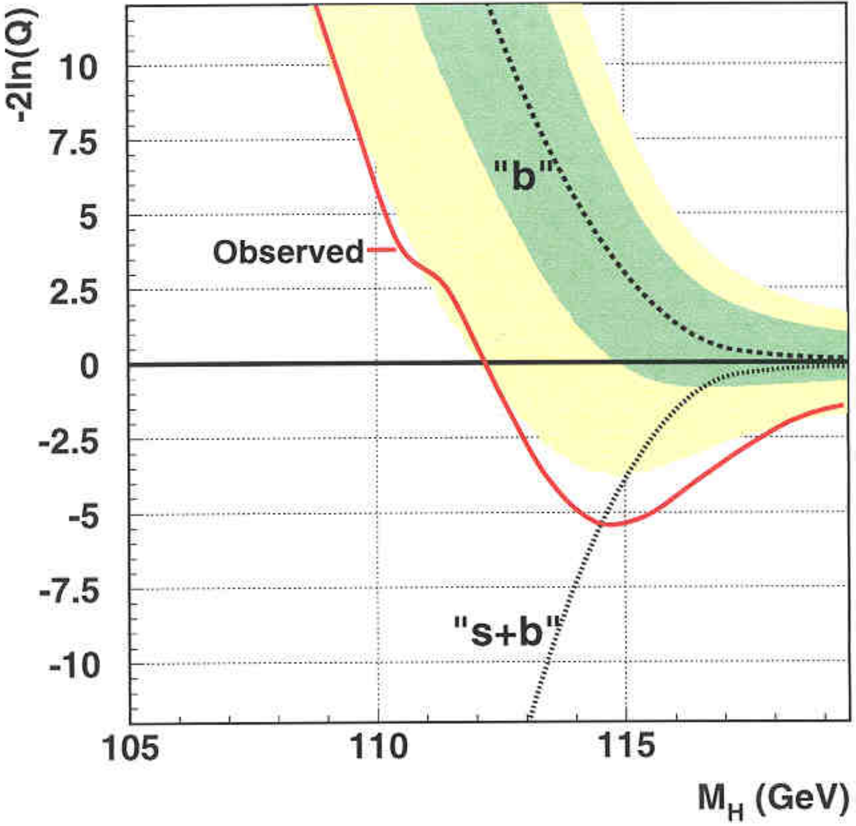
Likelihood ratio

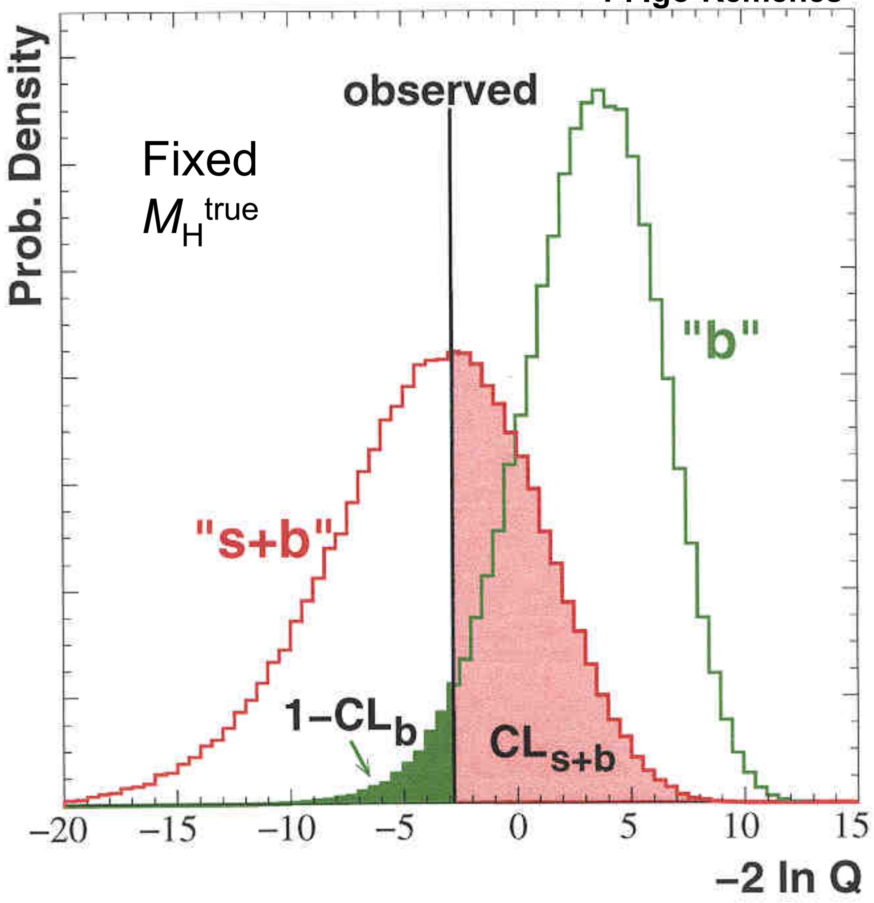
$$Q\left(M_{\mathrm{H}}^{\mathrm{true}}\right) = \frac{\mathrm{L}(s+b)}{\mathrm{L}(b)}$$

set of all events: *s*+*b* or *b* ?

$$-\ln Q = \sum_i s_i - \sum_i N_i \ln\left(1 + \frac{s_i}{b_i}\right)$$

Statistics


P. Igo-Kemenes


P. Igo-Kemenes

expected curves using MC instead of data

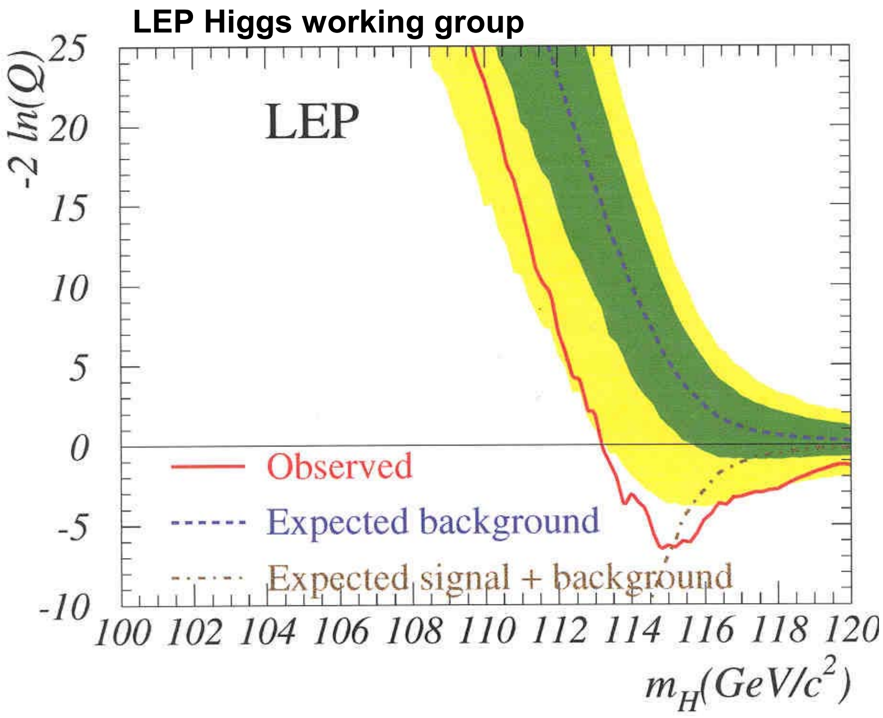
$1-CL_b$	0.32	0.046	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
$n\sigma$	1σ	2σ	3σ	4σ	5σ

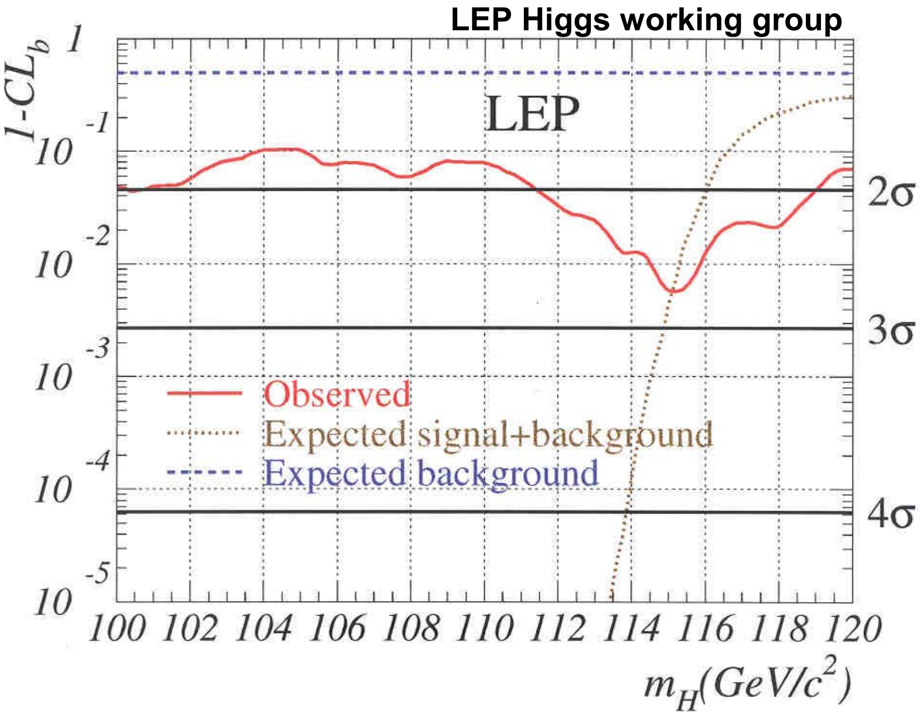
$1-CL_b$ measures compatibility with “b”

CL_{s+b} measures compatibility with “s+b”

$$CL_s = \frac{CL_{s+b}}{CL_b}$$ set lower bound on M_H

LEP SM Higgs Results



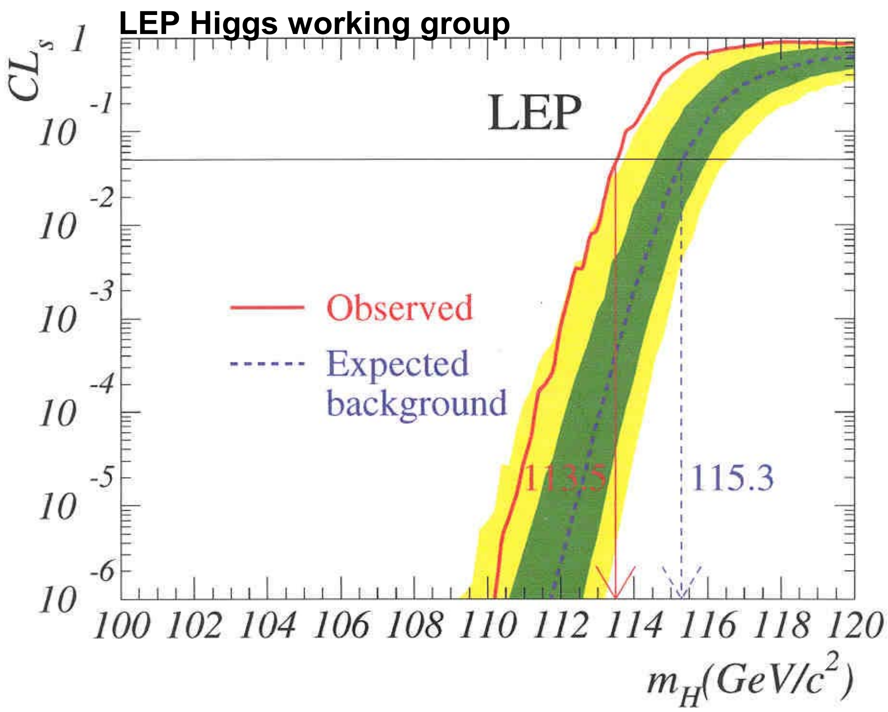


$$M_{\mathrm{H}} = 115.0^{+1.3}_{-0.9}\ \mathrm{GeV}$$

$$1 - CL_b = 2.9\sigma$$

Probability that what is observed is background is 0.4%

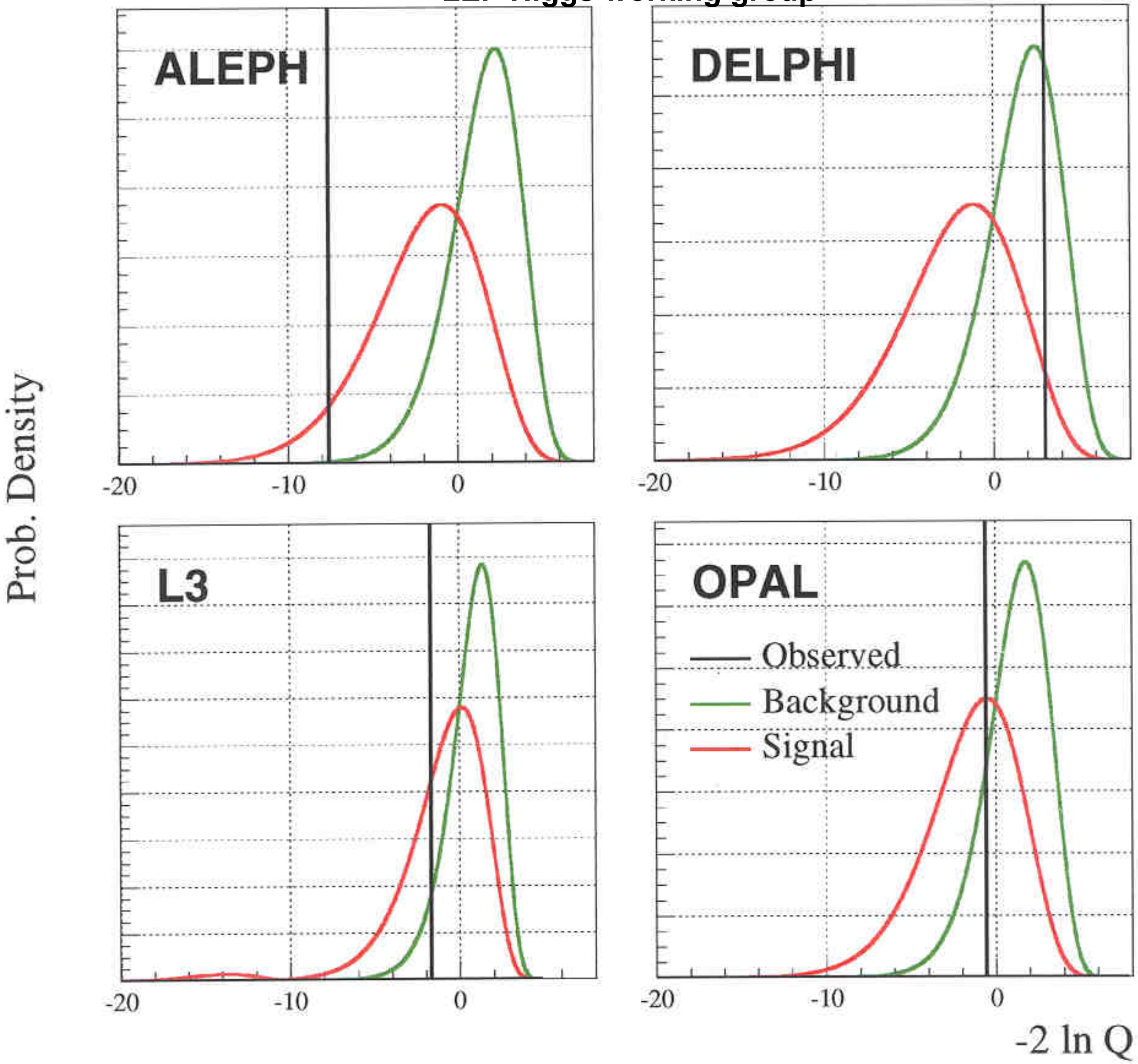
LEP SM Higgs Lower Bound



$$\boxed{M_H > 113.5\,\mathrm{GeV}\ @95\%\ \mathrm{CL}}$$

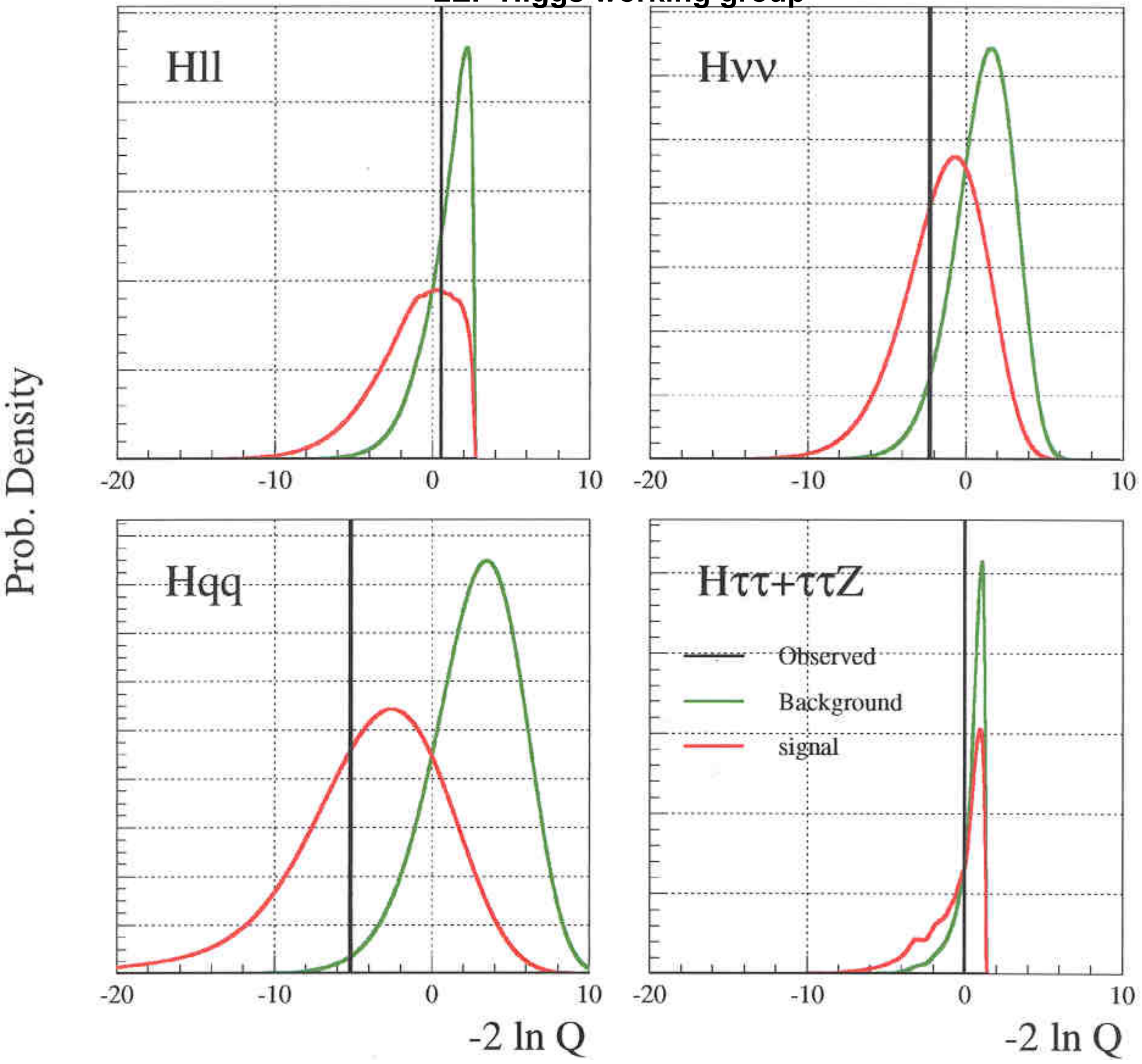
Probability Densities per Detector

LEP Higgs working group

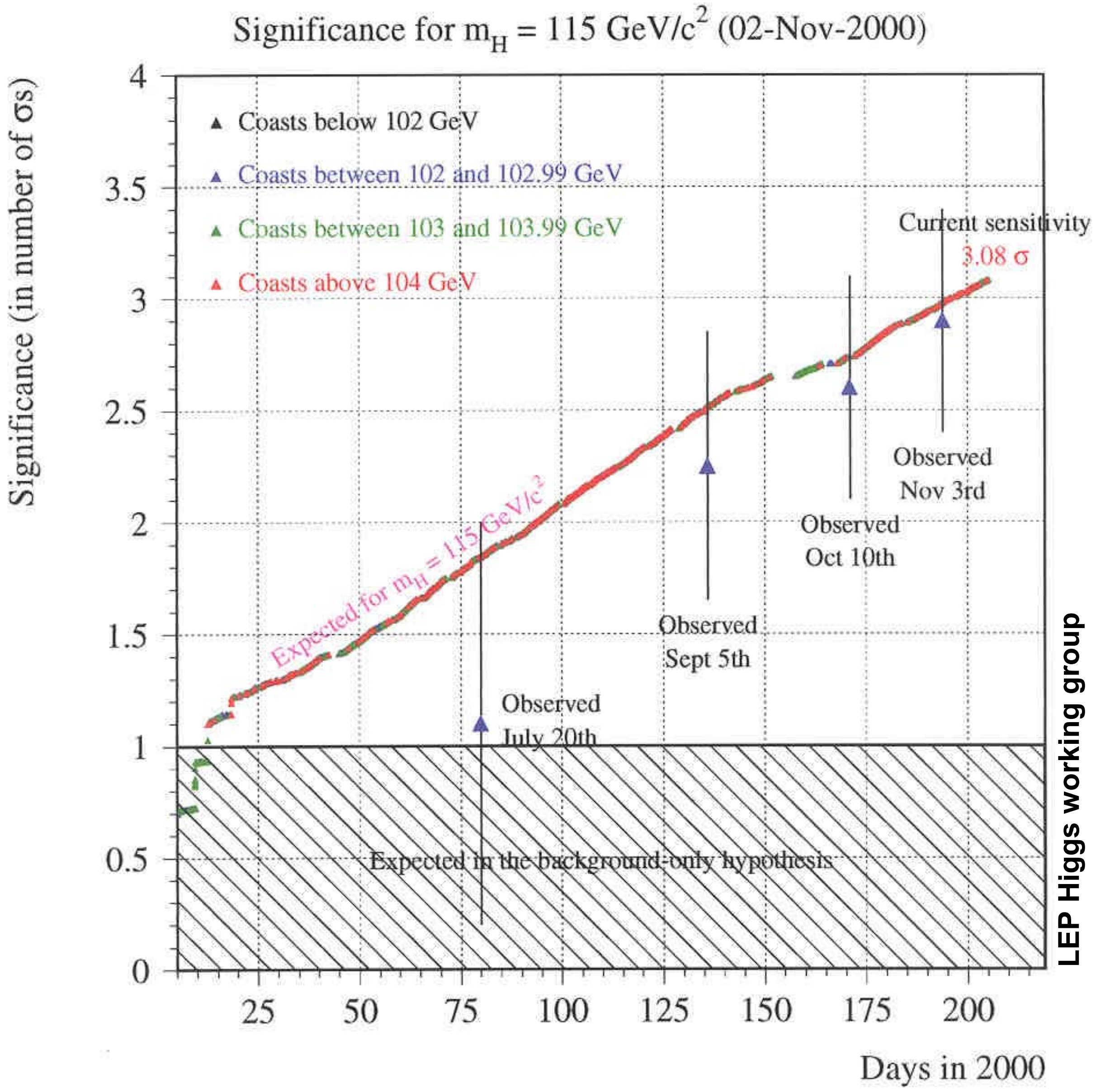


Probability Densities per Decay Mode

LEP Higgs working group



Evolution with Luminosity



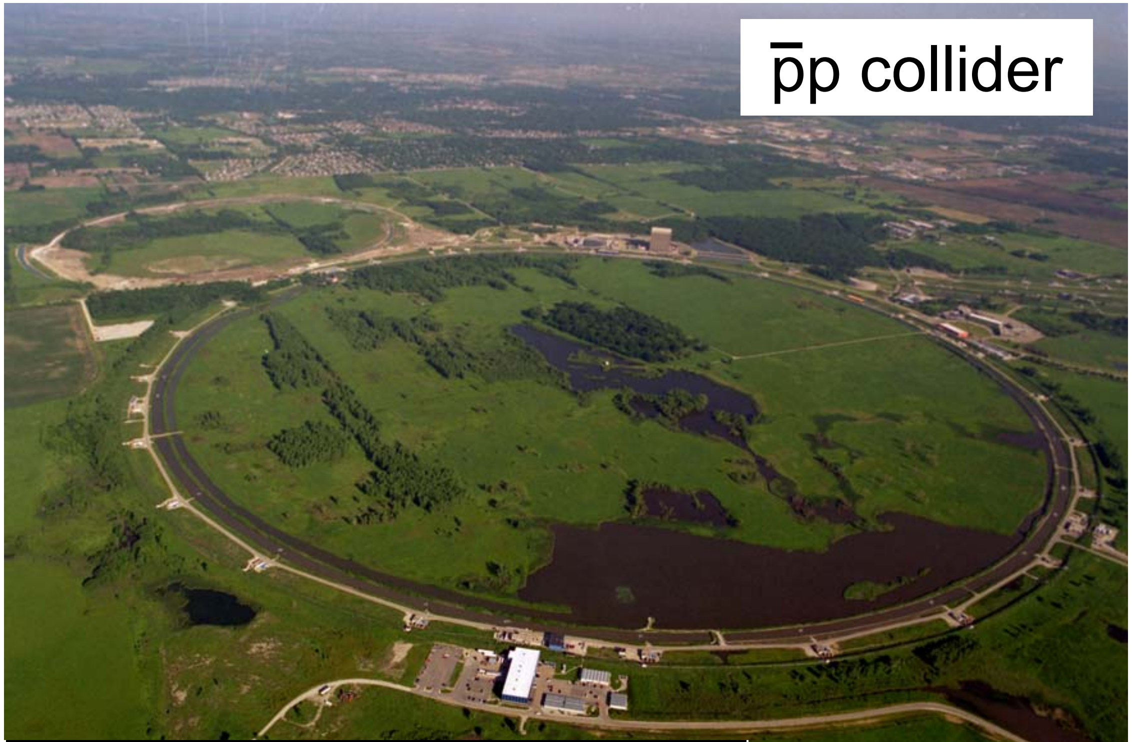
LEP Higgs working group

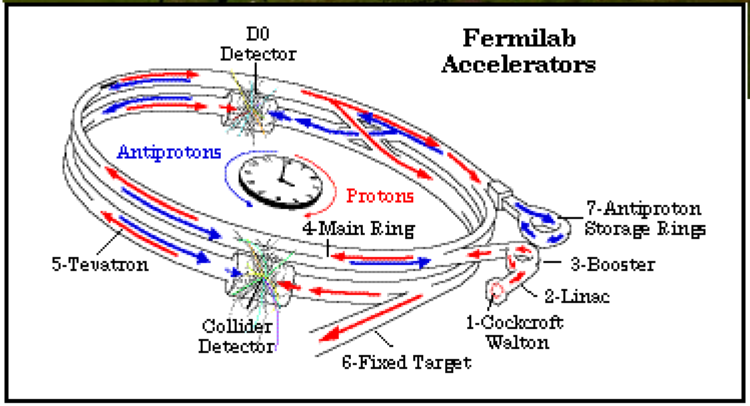
LEP community requested another 200 pb^{-1} in 2001 to reach 5σ

LEP is now being dismantled, to install the LHC

When will we know if LEP really detected a Higgs?

The Tevatron at Fermilab


$\bar{p}p$ collider



Run I $\sqrt{s}$ = 1.8 TeV

6+6 bunches, 3.5 μs
$\approx 1.6 \times 10^{31}$ cm^{-2}s^{-1}
$\approx$ 2 pb^{-1}week^{-1} per exp.

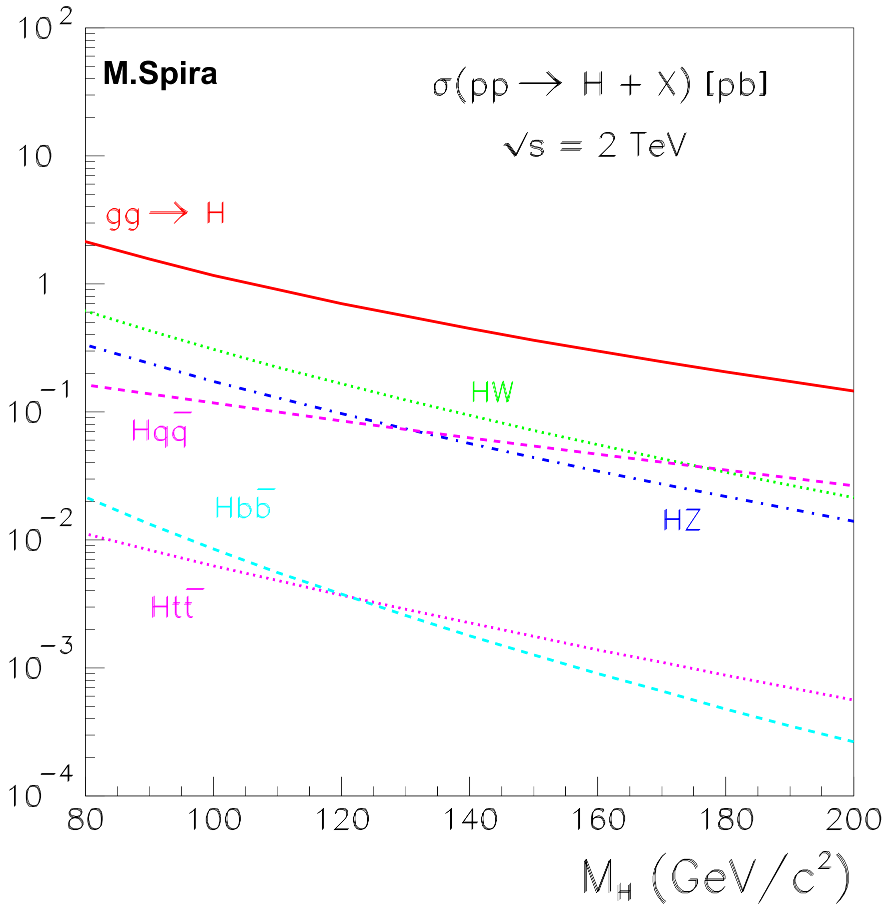
Run IIa $\sqrt{s}$ = 2.0 TeV

36+36 bunches, 396 ns
start March 1st 2001
goal, by end 2002
$\approx 2 \times 10^{32}$ cm^{-2}s^{-1}
>2 fb^{-1}per exp.

Run IIb $\sqrt{s}$ = 2.0 TeV

more bunches, 132 ns
goal, by end 2007
$\approx 5 \times 10^{32}$ cm^{-2}s^{-1}
>15 fb^{-1}per exp.

SM Higgs Production at the Tevatron



E. Barberis

typical cross-sections ($\sqrt{s} = 2$ TeV)

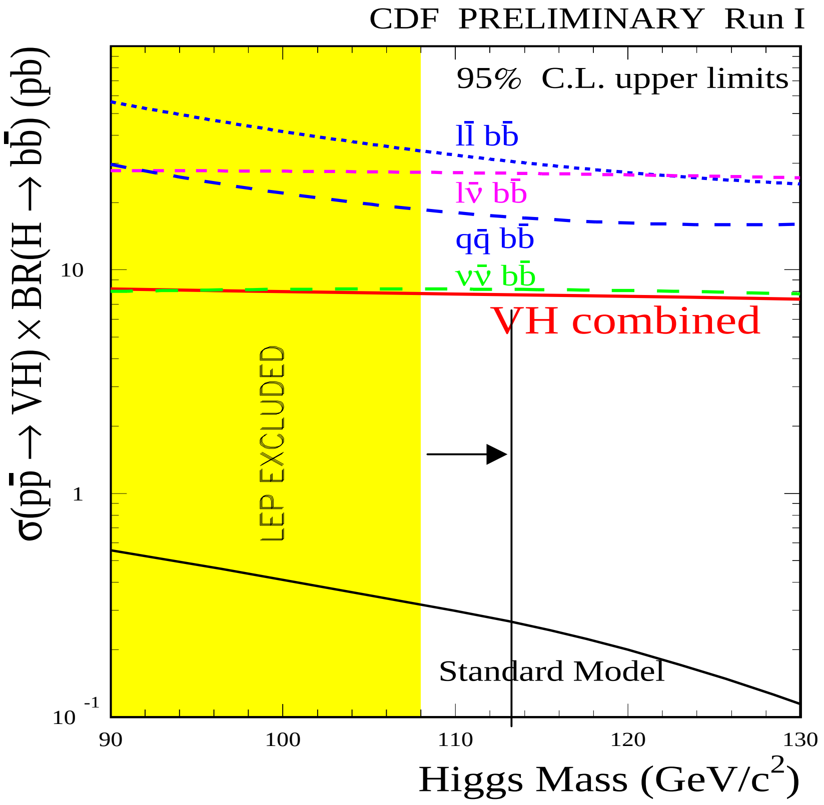
	σ[pb] (m_H=100 GeV)
$gg \to H$	1.0
WH	0.3
ZH	0.18
WZ	3.2
Wbb	11
tt	7.5
tb+tq+tbq	3.4
QCD	O(10^6)

WH/ZH production are preferred

SM Higgs Searches at the Tevatron

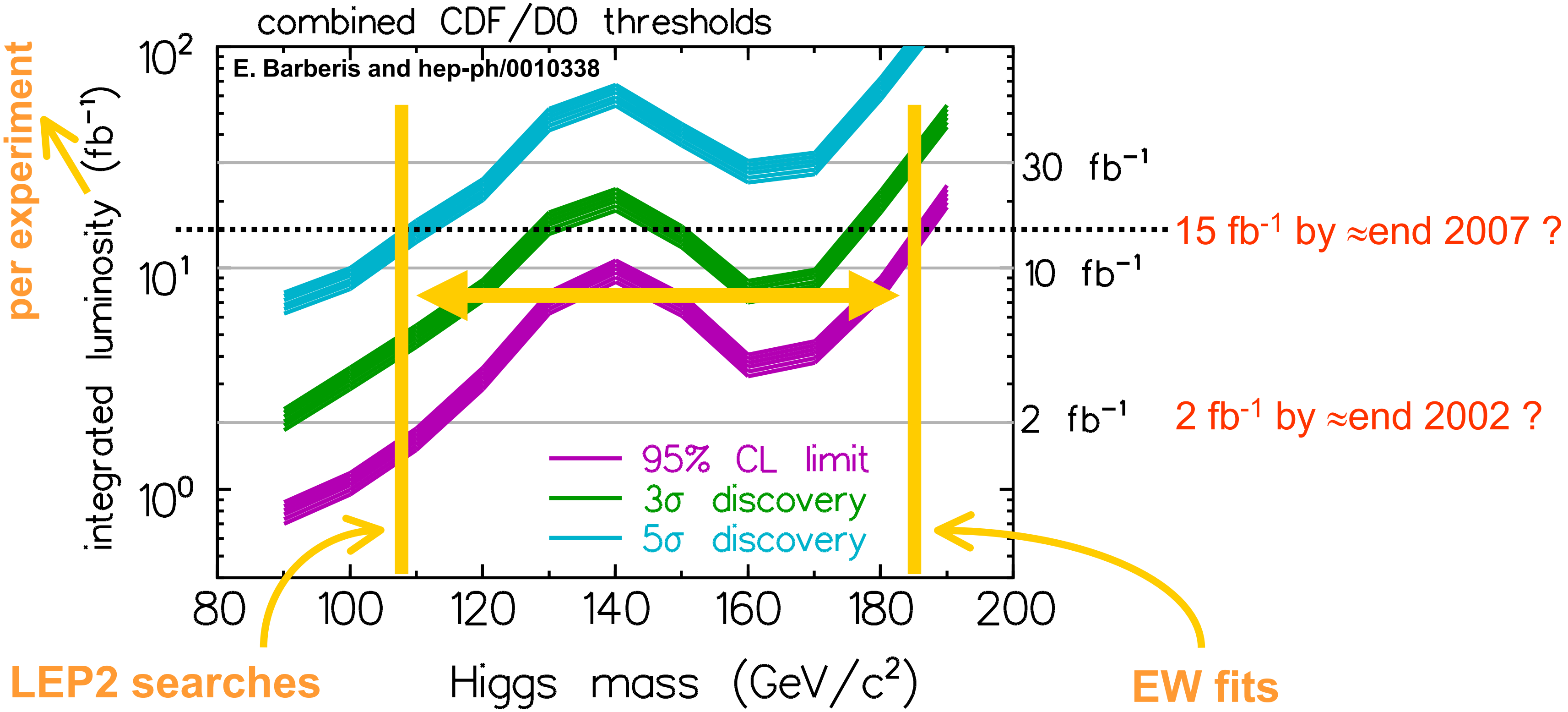
CDF: SVX b-tagging

$WH \to \nu\nu bb$	1 and 2 b-tag
$WH \to l\nu bb$	1 and 2 b-tag
$ZH \to \nu\nu bb$	1 and 2 b-tag
$ZH \to llbb$	1 b-tag



one order of magnitude
away from prediction

SM Higgs Discovery at the Tevatron



per experiment

$15\ fb^{-1}$ by ≈end 2007 ?

$2\ fb^{-1}$ by ≈end 2002 ?

LEP2 searches

EW fits

$2\ fb^{-1}$ 95% CL barely extend the LEP2 result

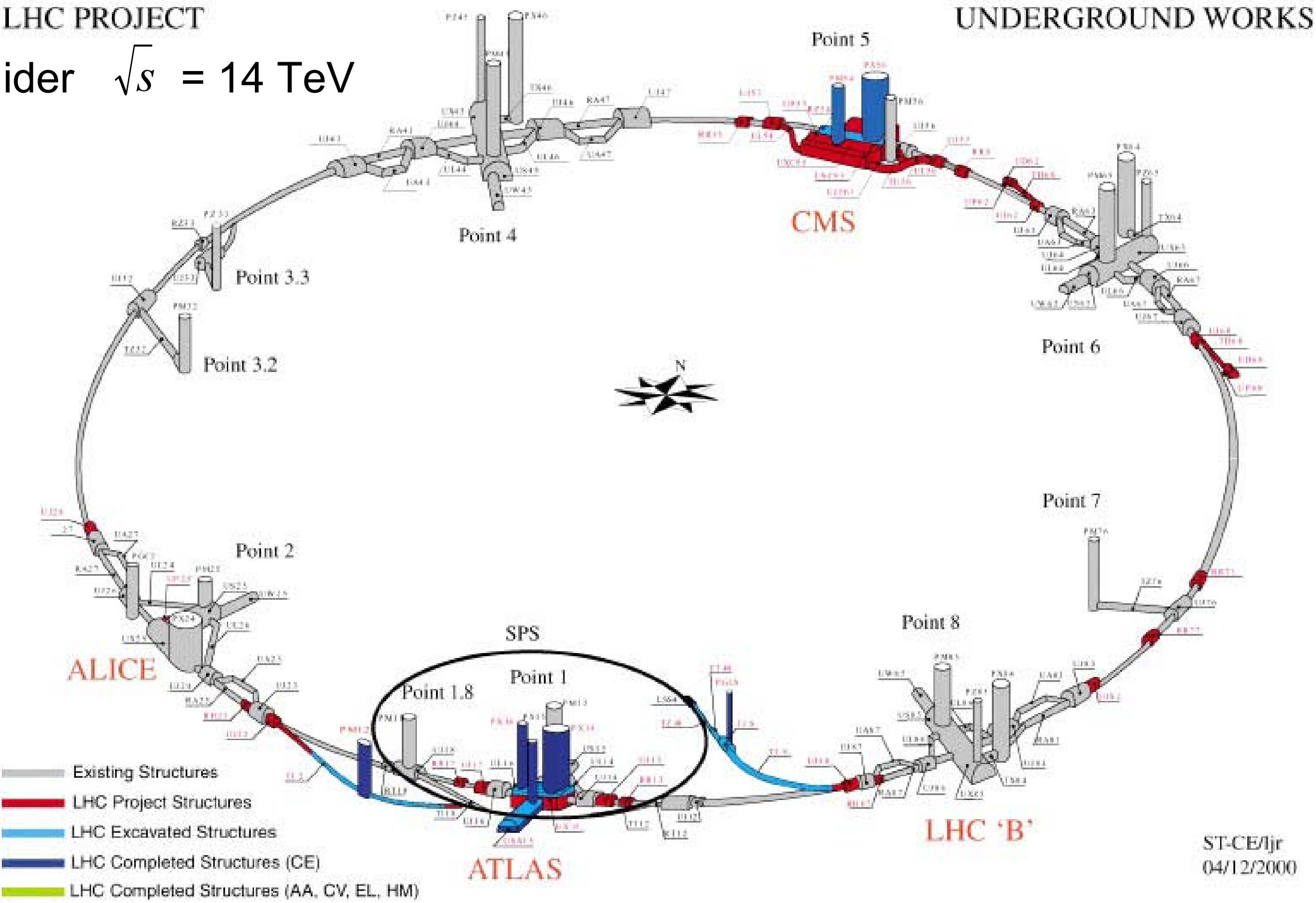
$10\ fb^{-1}$ 95% CL exclusion to M_H≈180 GeV in the absence of signal

$15\ fb^{-1}$ discovery potential for up to M_H≈115 GeV

Aerial View of CERN

Large Hadron Collider at CERN

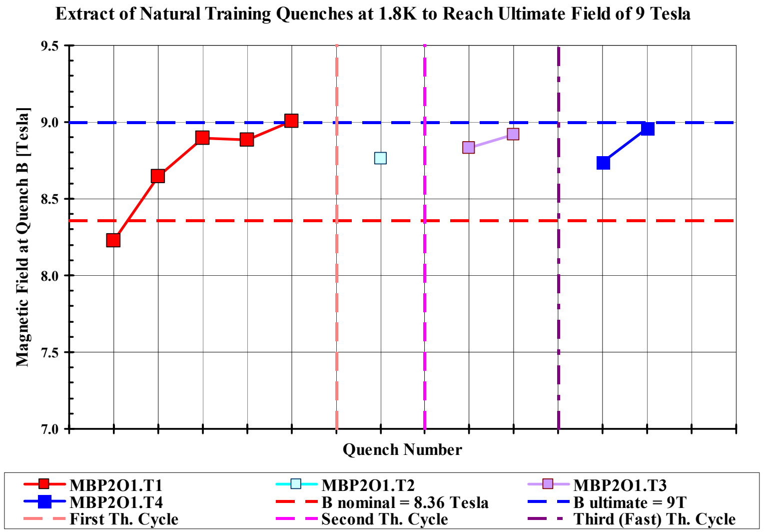
pp collider $\sqrt{s}$ = 14 TeV



Large Hadron Collider at CERN

pp collider $\sqrt{s}$ = 14 TeV

2835+2835 bunches, 25 ns
octan test in 2004
ring cooled by end 2005
beam for physics 2006
$\approx 2\times10^{33}$ $\mathrm{cm^{-2}s^{-1}}$ after 7 months
latest: 10 $\mathrm{fb^{-1}}$ by March 2007
expect 10 $\mathrm{fb^{-1}}$/y for first 3 years
design: 1×10^{34} $\mathrm{cm^{-2}s^{-1}}$, 100 $\mathrm{fb^{-1}}$/y



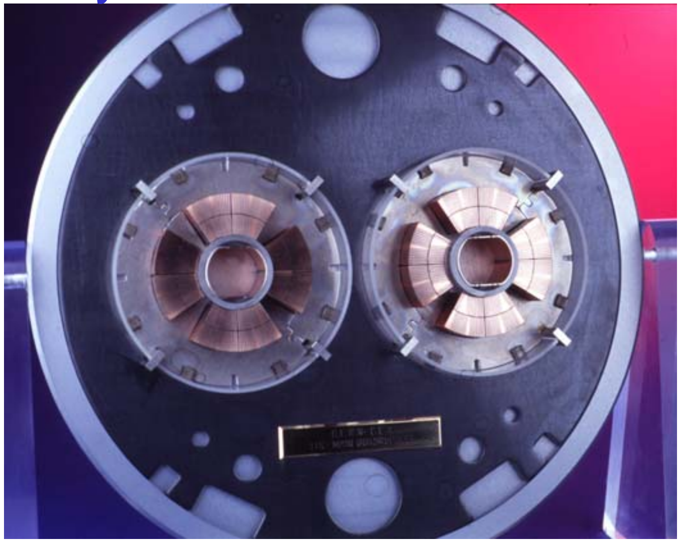
5000 superconducting magnets (1296 dipoles)
Cu-clad Nb-Ti cables to operate at 1.9K with up to 15kA

Dipole field of 8.36T
(Tevatron 4.5T, HERA, 5.5T)
"Contracts for all main components of dipoles are now placed and series production has started". L.R. Evans, Scientific Policy Comitte, CERN, 11/12/2000

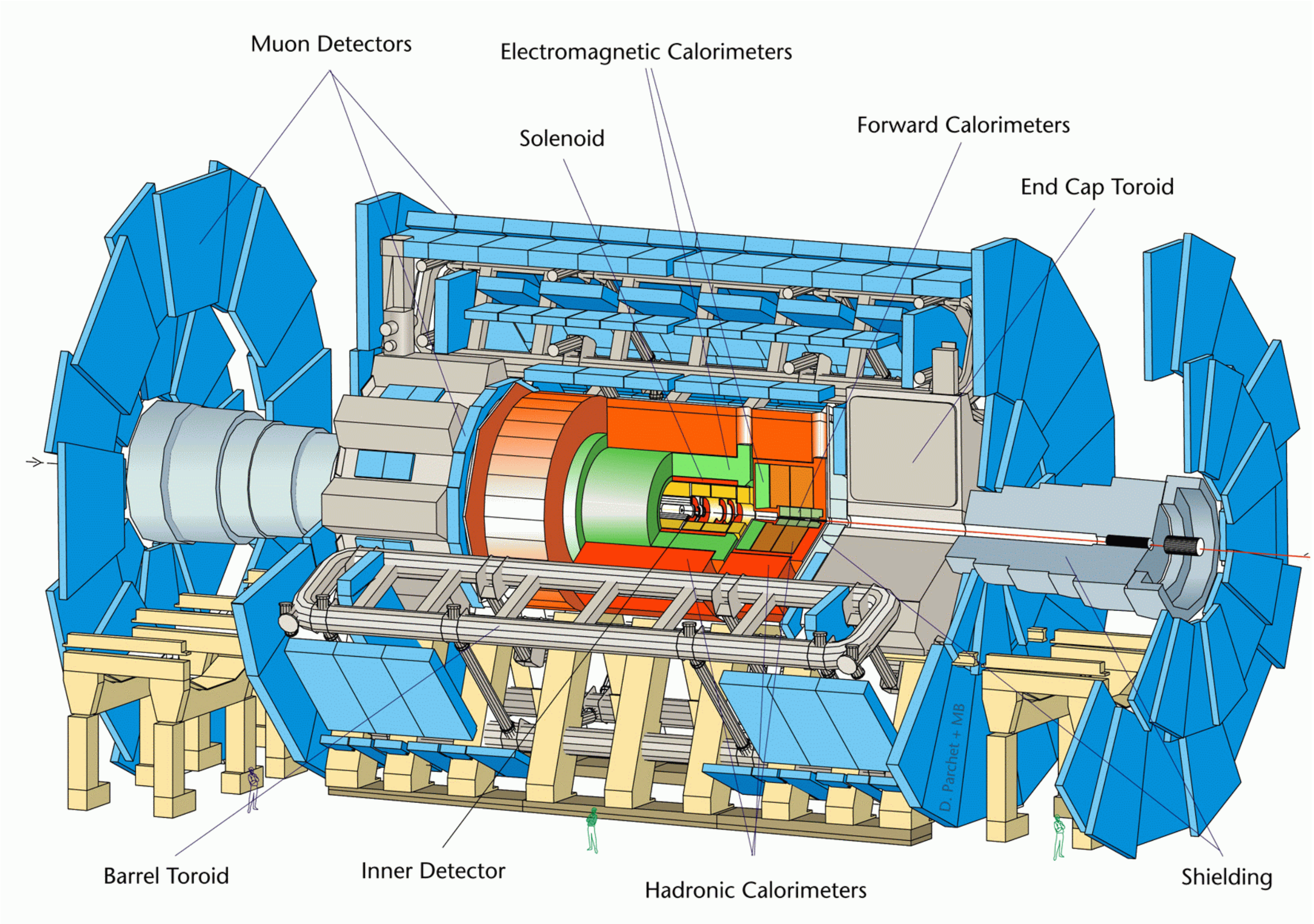
LHC: 25×E and 10k×L of SPS for same power


Point 1 - UX15 vault - view towards PX14 shaft - November 03, 2000 - CERN

ATLAS pit
3/11/2000



The ATLAS Detector

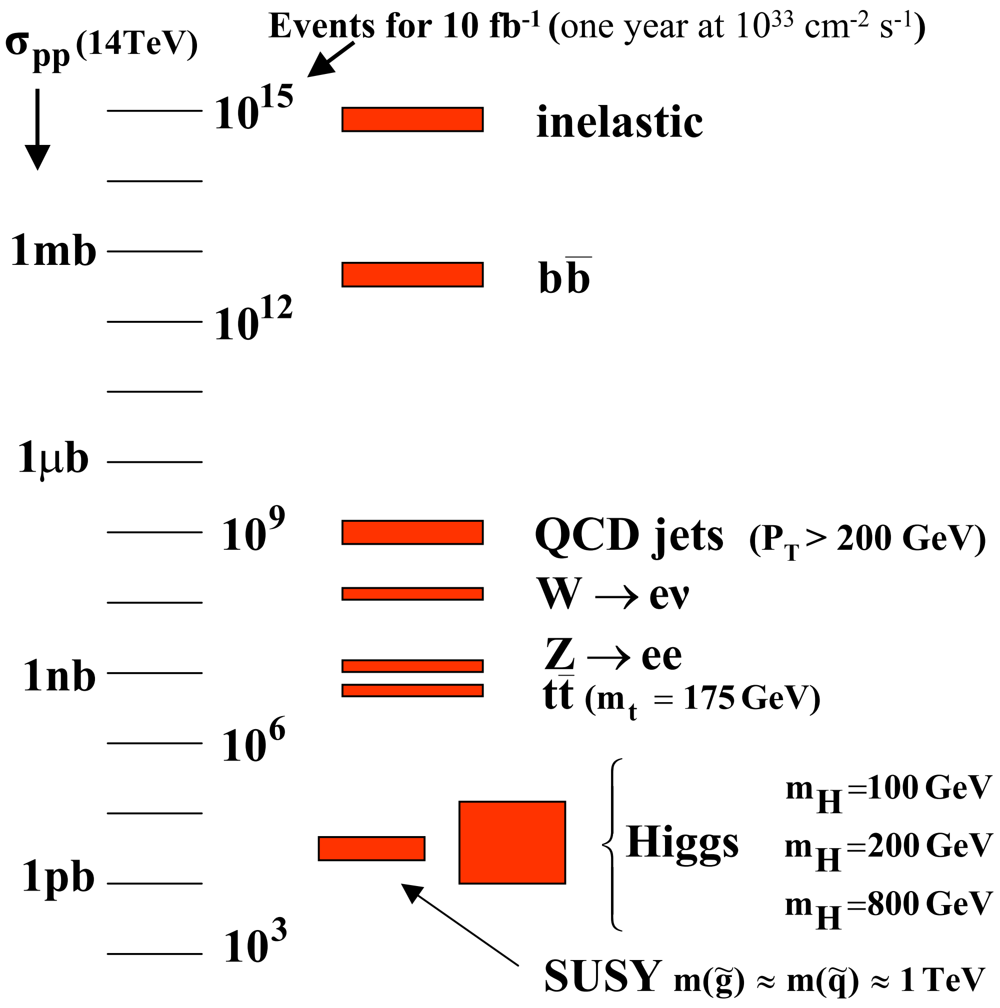


Alberta
Carleton
CRPP
Montréal
Toronto
TRIUMF
UBC
Victoria
York

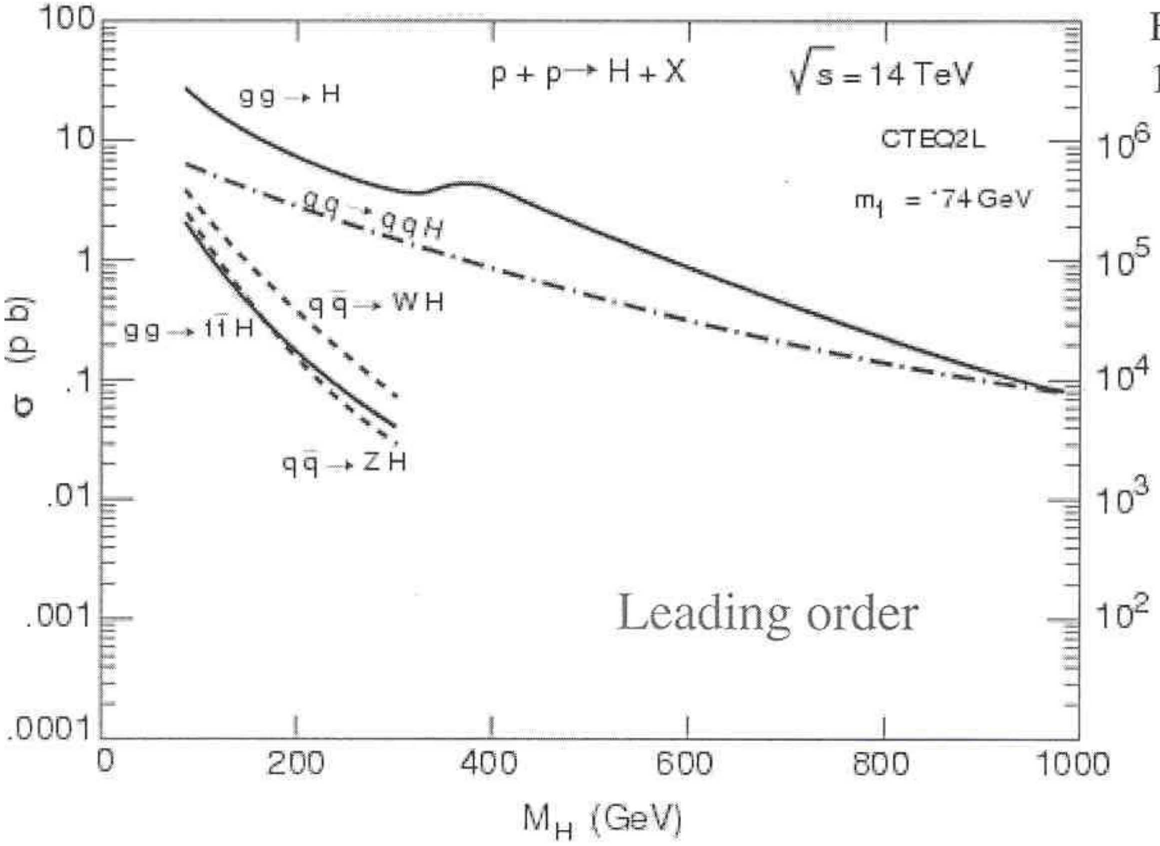
UVic graduates

J. White (M.Sc. 93)
S. Robertson (M.Sc. 94)
S. Bishop (M.Sc. 95)
D. O'Neil (Ph.D. 99)
D. Fortin (M.Sc. 00)
M. Dobbs (Ph.D.)

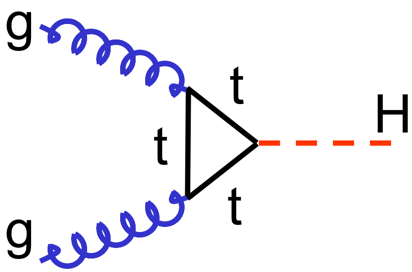
LHC PP Cross Section

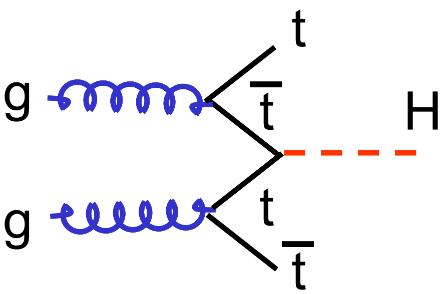


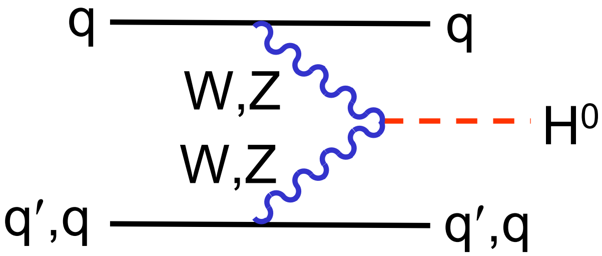
SM Higgs Production at the LHC

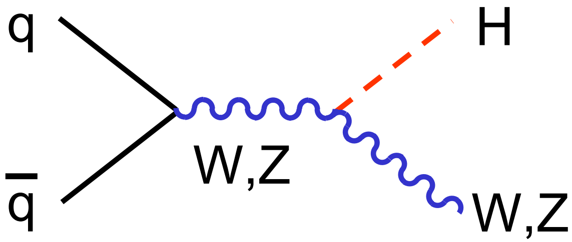


Events for
100 fb^{-1} (one year at 10^{34} cm^{-2} s^{-1})









Main SM Higgs Search Channels

Large QCD backgrounds:

$$\sigma\left(H \to b\bar{b}\right) \approx 20\ \text{pb}$$

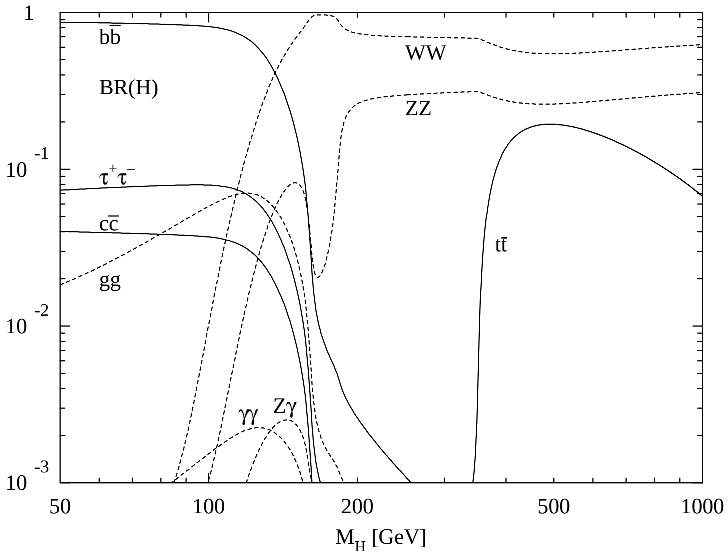
$$\sigma\left(b\bar{b}\right) \approx 500\ \mu\text{b}$$

M_H=120 GeV, direct production

No hope to trigger on or extract fully hadronic final states

Look for final states with photons and leptons

Detector performance is crucial: b-tag, γ/l *E*-resolution, γ/j separation, missing energy resolution, forward jet tag,...



$M_H < 2M_Z$

- $t\bar{t}H \to l\,b\bar{b} + X$ **large backgrounds**
- $H \to \gamma\gamma$ **low branching ratio**
- $H \to ZZ^* \to 4l$
- $H \to WW^* \to l\,\nu\,l\,\nu$

$M_H > 2M_Z$

- $H \to ZZ \to 4l$ **Gold-plated channel!**
- $H \to ZZ \to l\,l\,\nu\,\nu$
- $H \to ZZ \to l\,l\,j\,j$
- $H \to WW \to l\,\nu\,j\,j$

$$\left.\begin{array}{l} H \to ZZ \to l\,l\,\nu\,\nu \\ H \to ZZ \to l\,l\,j\,j \\ H \to WW \to l\,\nu\,j\,j \end{array}\right\}$$

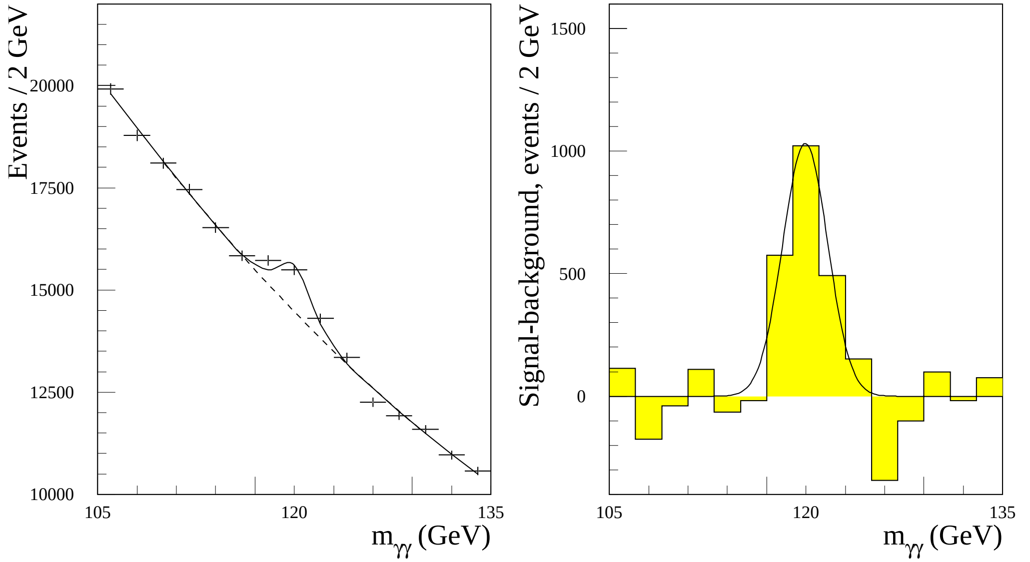
M_H > 300 GeV forward jet tag

$H\to\gamma\gamma$ at ATLAS

Signal $\sigma\times\mathrm{BR}=43\ \mathrm{fb}\ (m_H=100\ \mathrm{GeV})$

$\gamma\gamma$ background (irreducible) $\dfrac{d\sigma}{dm_{\gamma\gamma}}\sim 1200\ \mathrm{fb/GeV}\ (m_{\gamma\gamma}=100\ \mathrm{GeV})$

QCD jet background $\dfrac{\sigma_{\gamma,j}}{\sigma_{\gamma\gamma}}\sim 1000,\quad \dfrac{\sigma_{j,j}}{\sigma_{\gamma\gamma}}\sim 2\times10^{6}$ **(reducible)**



m_H (GeV)	100	120	140
signal events	960	1200	930
$\gamma\gamma$ background	44700	30300	20800
γ - jet, jet - jet background	6700	4400	3900
Statistical significance	4.7σ	6.9σ	6.3σ

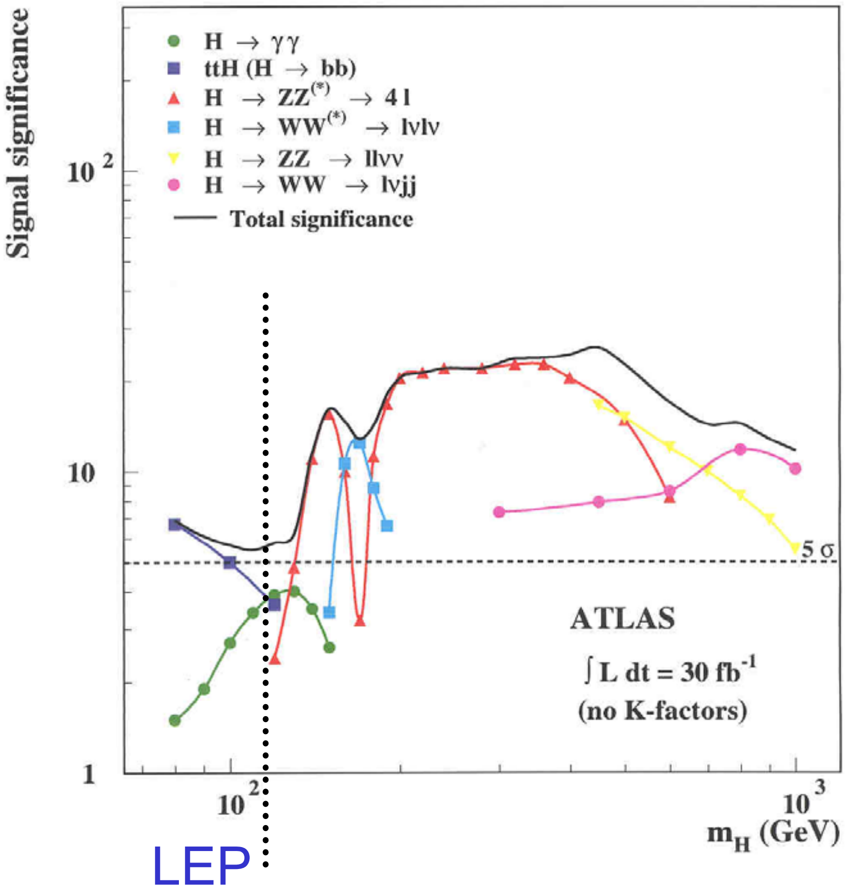
Analysis:

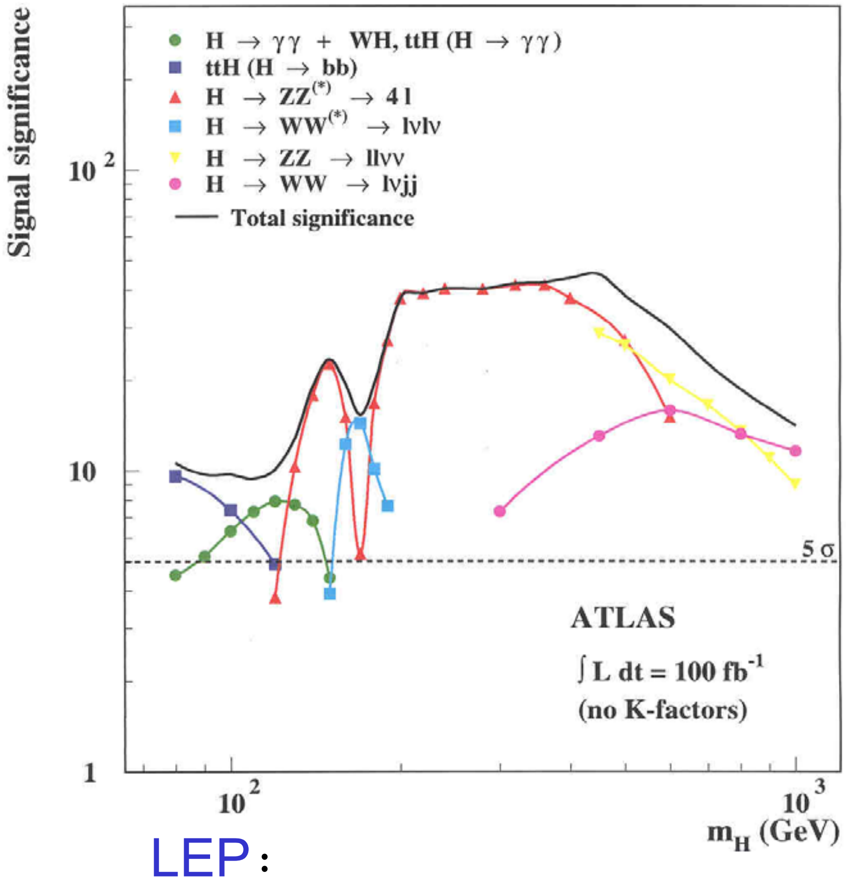
Two isolated γ's: $p_T^1>40$ GeV, $p_T^2>25$ GeV, $|\eta|<2.5$

Good γ/jet separation: QCD jet background at the level of 10 to 20% of the irreducible $\gamma\gamma$ background

Good mass resolution: $\sigma_m=1.3$ GeV for $m_H=100$ GeV

ATLAS SM Higgs Discovery Potential



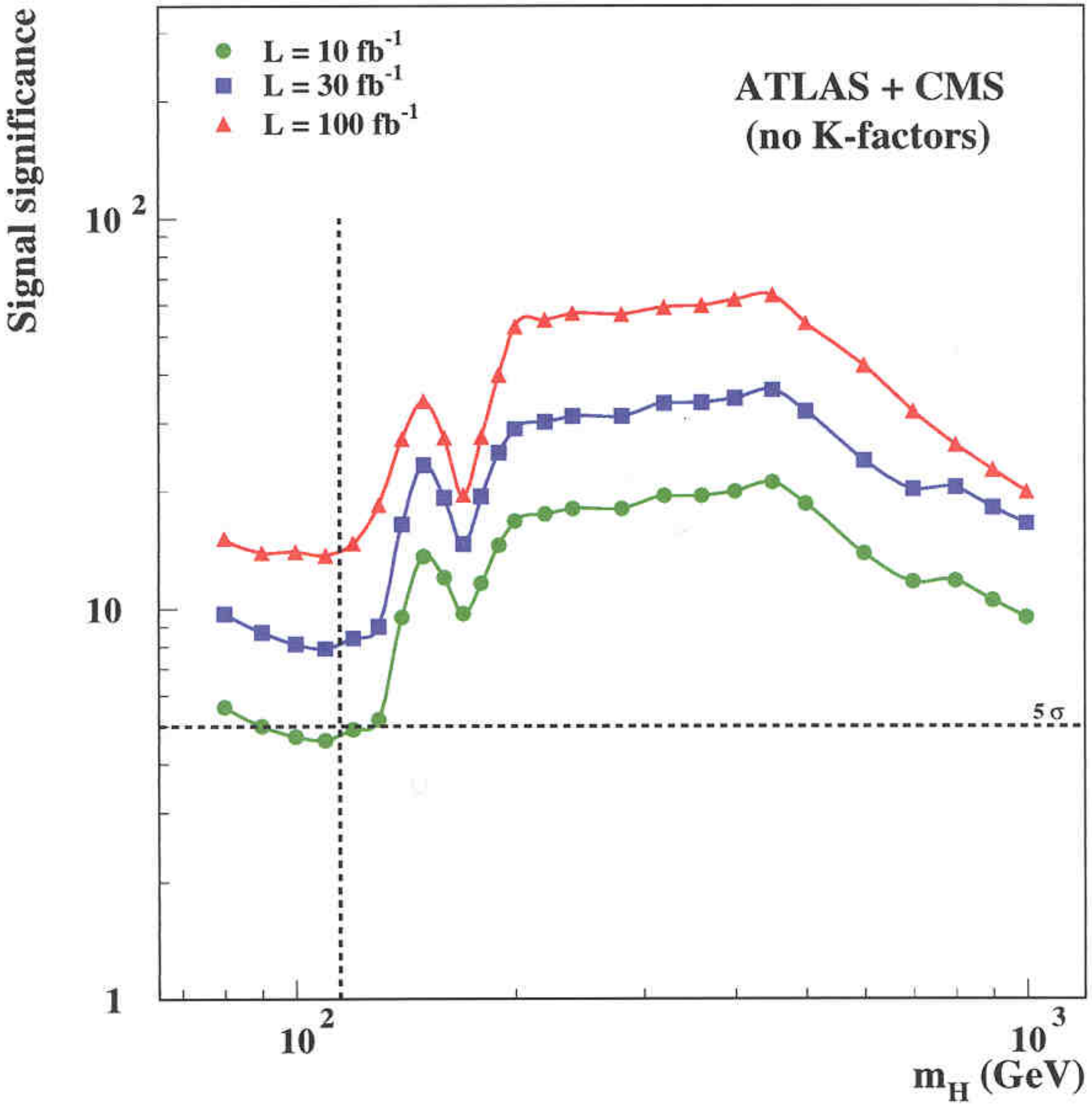


SM Higgs can be discovered over full mass range with 30 fb^{-1}

In most cases, more than one channel is available.

Signal significance is S/B$^{1/2}$ or using Poisson statistics

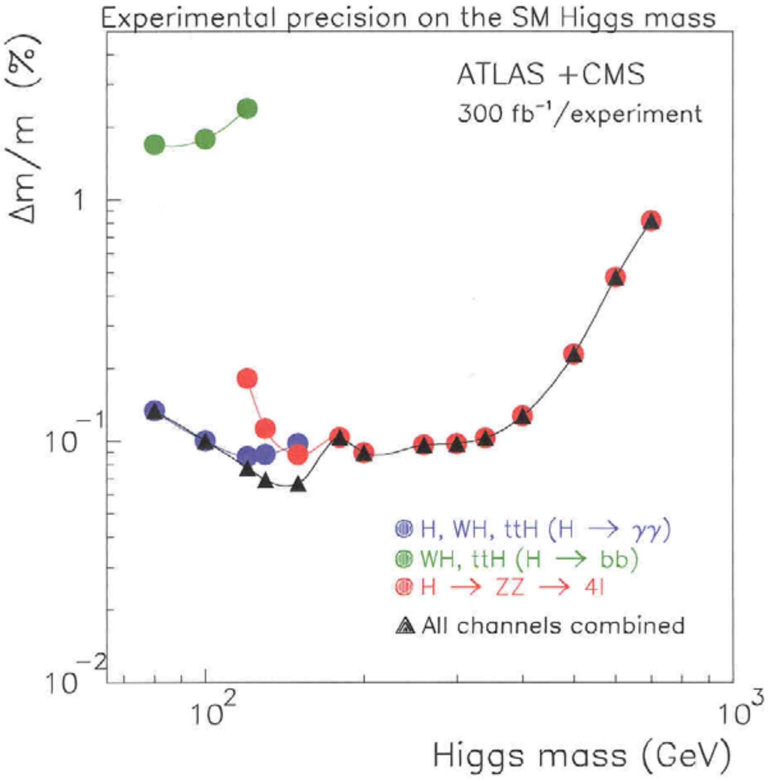
LHC SM Higgs Discovery Potential

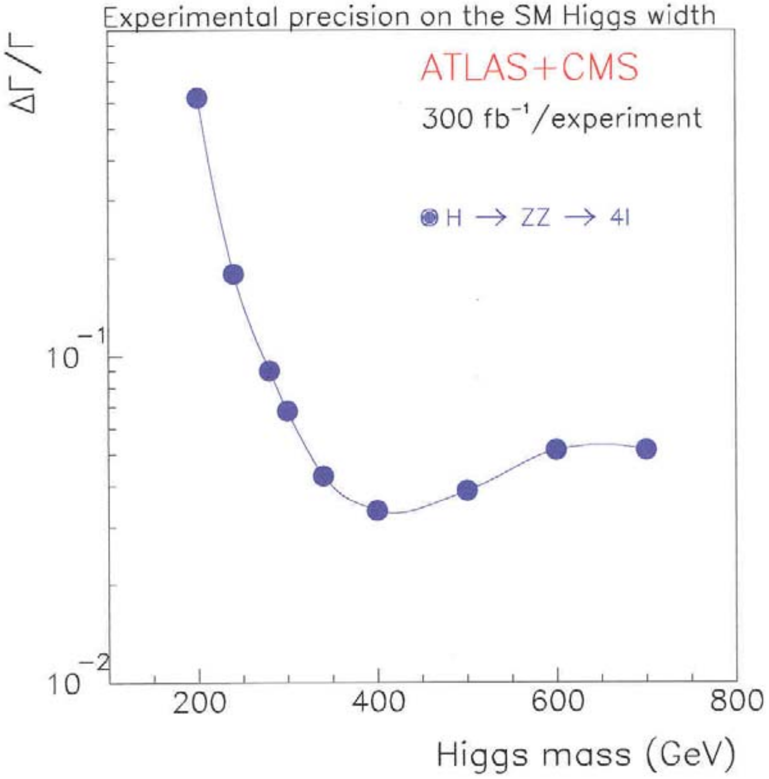


need 10 fb^{-1} for 5σ 115 GeV Higgs discovery (during 2007)

larger masses is much easier!

SM Higgs Mass and Width





Beyond the Standard Model

In principle, if $130\,\text{GeV} \approx< M_\text{H} \approx< 180\,\text{GeV}$ then the SM is viable to M_PL

But, SM one loop corrections

$$M_\text{H}^2 = \left(M_\text{H}^2\right)_0 + bg^2\Lambda^2 \qquad b \sim O(1) \qquad \left(M_\text{H}\right)_0 \text{ is parameter of fundamental theory}$$

The "natural" value for M_H is $g\Lambda$, which leads to the expectation

$$\Lambda \sim \frac{M_\text{H}}{g} \sim O(1\,\text{TeV})$$

If Λ >> 1 TeV, need "unnatural" tuning

Beware… what seems unnatural today...

$$\frac{\left(M_\text{H}^2\right)_0}{\Lambda^2} = \frac{M_\text{H}^2}{\Lambda^2} - g^2$$

If $\Lambda = M_\text{PL}$, need adjustment to the 38th decimal place!!!

Violation of naturalness = hierachy problem

Low-energy **supersymmetry** is a way out...

Not the only way out…
extra dimensions!

Supersymmetry

$$\left.\begin{array}{l}\left.\begin{array}{l}\left.\begin{array}{l}\textbf{3D rotations}\\ \textbf{pure boosts}\end{array}\right\}\textbf{Lorentz}\\ \textbf{4D translations}\end{array}\right\}\textbf{Poincare}'\\ \textbf{SUSY translations}\end{array}\right\}\textbf{superPoincare}'$$

Maximal extension of the Poincaré group

SUSY actions are invariant under superPoincaré

they are composed of an equal number of bosonic and fermionic degrees of freedom

SUSY mixes fermions and bosons

exact SUSY ⟹ there should exist fermions and bosons of the same mass
clearly NOT the case ⟹ SUSY IS BROKEN ⟹ WHY BOTHER WITH SUSY??

A solution to the hierarchy problem

If the Higgs is to be light without unnatural fine tuning, then (softly broken) SUSY particles should have M_{SUSY}<~ 1 TeV. SUSY can be viable up to M_{PL} AND be natural!

GUT acceptable coupling constant evolution

The precision data at the Z mass (LEP and SLC) are inconsistent with GUT's using SM evolution, but are consistent with GUT's using SUSY evolution, if $M_{\mathrm{SUSY}} \approx 1$ TeV

A natural way to break EW symmetry

The large top Yukawa coupling can naturally drive the Higgs quadratic coupling negative in SUSY

Lightest SUSY particle is a cold dark matter candidate

Local SUSY is SUperGRAvity

Minimal SUSY Higgs Sector

MSSM: SM + an extra Higgs doublet + SUSY partners

SUSY breaking

0	H_d^-	H_d^0	H_u^0	H_u^+						$\tilde{q}_R^d$	$\tilde{q}_L^d$	$\tilde{q}_R^u$	$\tilde{q}_L^u$	$\tilde{\nu}_L$	$\tilde{l}_R$	$\tilde{l}_L$
$\frac{1}{2}$	$\tilde{H}_d^-$	$\tilde{H}_d^0$	$\tilde{H}_u^0$	$\tilde{H}_u^+$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{W}^-$	$\tilde{W}^+$	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_L	l_R	l_L
1					B^0	W^0	W^-	W^+	g							

EW symmetry breaking

0	A	H	h	H^-	H^+					$\tilde{q}_2^d$	$\tilde{q}_1^d$	$\tilde{q}_2^u$	$\tilde{q}_1^u$	$\tilde{\nu}_l$	$\tilde{l}_2$	$\tilde{l}_1$
$\frac{1}{2}$	χ_4^0	χ_3^0	χ_2^0	χ_1^0	χ_2^-	χ_1^-	χ_2^+	χ_1^+	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_l	l_R	l_L
1					Z^0	γ	W^-	W^+	g							

⟶ **5 massive Higgs particles, with $M_h < 130$ GeV**

At tree level, all Higgs boson masses and couplings can be expressed in terms of two paramerets only (in "constrained MSSM")

$$m_A \quad \text{and} \quad \tan\beta = \frac{\text{vev } H_u}{\text{vev } H_d}$$

Note that we also have the following mixings

$$B^0, W^0 \rightarrow \gamma, Z^0$$

$$\tilde{W}^\pm, \tilde{H}^\pm \rightarrow \chi_{1,2}^\pm$$

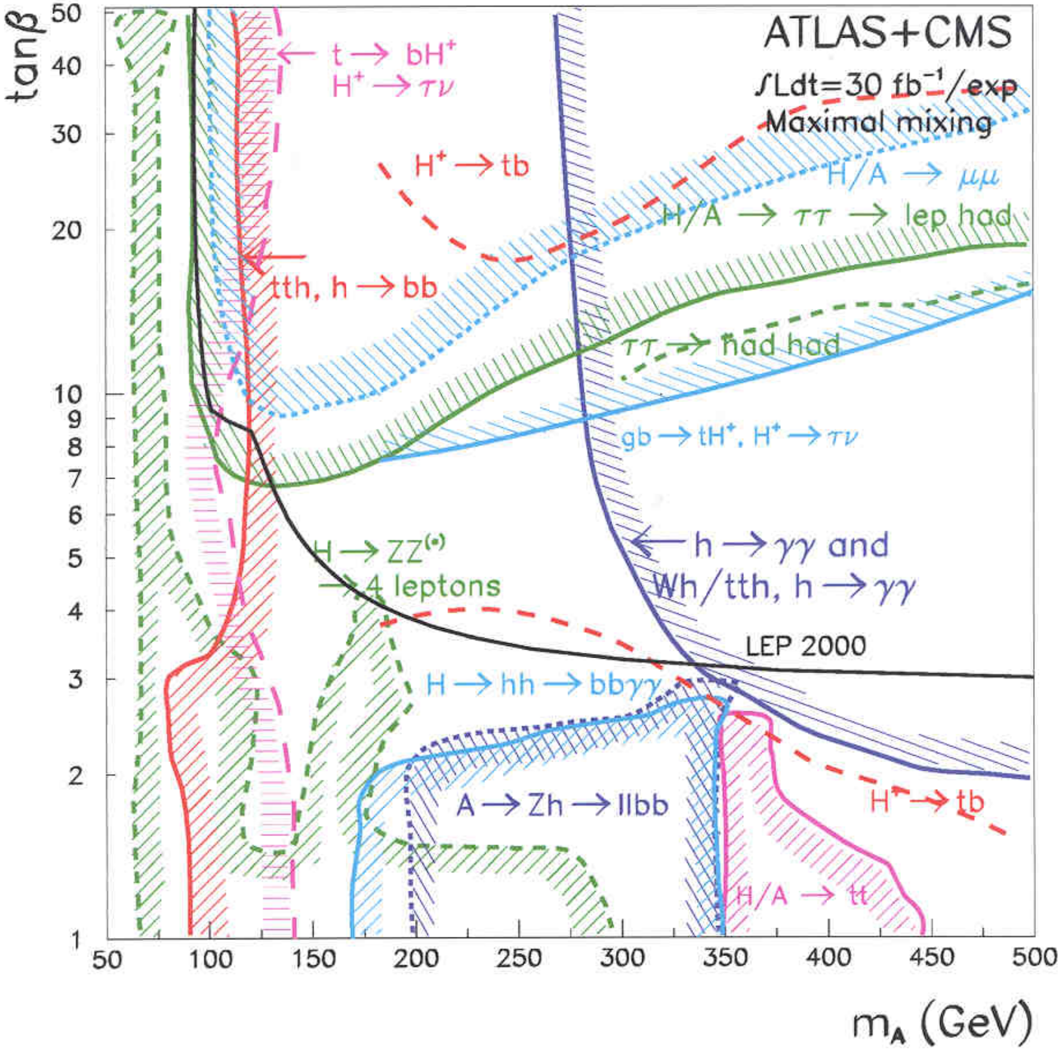
$$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \rightarrow \chi_{1,2,3,4}^0$$

$$\tilde{l}_L, \tilde{l}_R \rightarrow \tilde{l}_1, \tilde{l}_2$$

$$\tilde{q}_L, \tilde{q}_R \rightarrow \tilde{q}_1, \tilde{q}_2$$

with off-diagonal elements proportional to fermion masses

LHC MSSM Higgs Search



Full parameter space covered, SM and MSSM can be distinguished for almost all cases

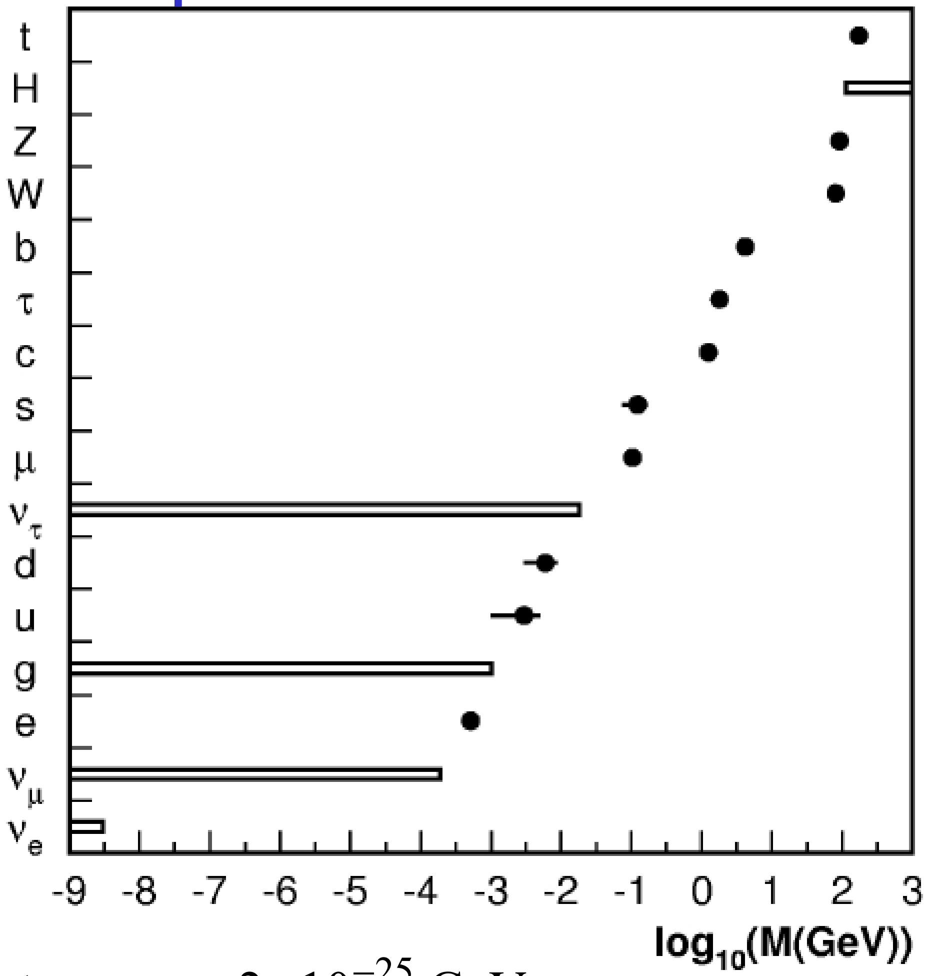
Most part of the parameter space covered by at least two channels, except low m_A region (covered by LEP200)

if h was “seen” at LEP200:
A/H should be observable at LHC for m_A<~ 2 m_{top}

If A or h was “seen” at LEP200: the charged Higgs should be seen at LHC

Fundamental Mass Values

Experimental values or limits



← $m_\gamma < 2\times10^{-25}$ GeV

The SM does not say anything about the origin of the VALUES of the masses… They have to be obtained from EXPERIMENT

exception: photons and gluons are predicted to be massless

Why such a large range of fundamental masses?

Indirect searches yield very small neutrino masses… why are neutral fermions so light?

Conclusions

The SM Higgs sector still requires direct experimental verification

Origin of electroweak symmetry hiding
Origin of mass

LEP results tantalizing

$M_{\mathrm{H}} = 115.0^{+1.3}_{-0.9}\ \mathrm{GeV}$ if signal hypothesis valid… 2.9 σ

$M_{\mathrm{H}} > 113.5\ \mathrm{GeV}\ @95\%\ \mathrm{CL}$

Must now wait for the Tevatron and the LHC

If M_{H} ~ 115 GeV	both Tevatron and LHC may discover it in ~2007
If M_{H} larger	then LHC rules

New physics at O(1 TeV) very likely, supersymmetry is a big favorite

This is going to be a very exciting decade !