Status of Higgs Particle Searches

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Theoretical considerations

Standard Model Higgs searches

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

Beyond the SM: Supersymmetry

Conclusions

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Status of Higgs Particle Searches

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 minimal supersymmetric extension of the SM yields five Higgs particles.

The search for the Higgs is central to many particle physics efforts. After a brief theoretical introduction, the status of the search for the Higgs (LEP and Tevatron) and prospects for future discoveries (Tevatron and LHC) are summarized.

Theory: gauge invariance, interactions, mass term

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

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

Consider the free Maxwell field $\mathcal{L}_M = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \qquad F^{\mu\nu}(x) \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$

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

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

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

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

Try to add a mass term to the Maxwell field ⟹ $\frac{1}{2} M^2 A^\mu A_\mu$

⟹ This violates $U(1)_Q$ gauge invariance!!

In the SM, the EW interaction is from $U(1)_Y \times SU(2)_L$ gauge invariance

⟹ **ALL ad hoc mass terms violate gauge invariance in the SM**

Theory: 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

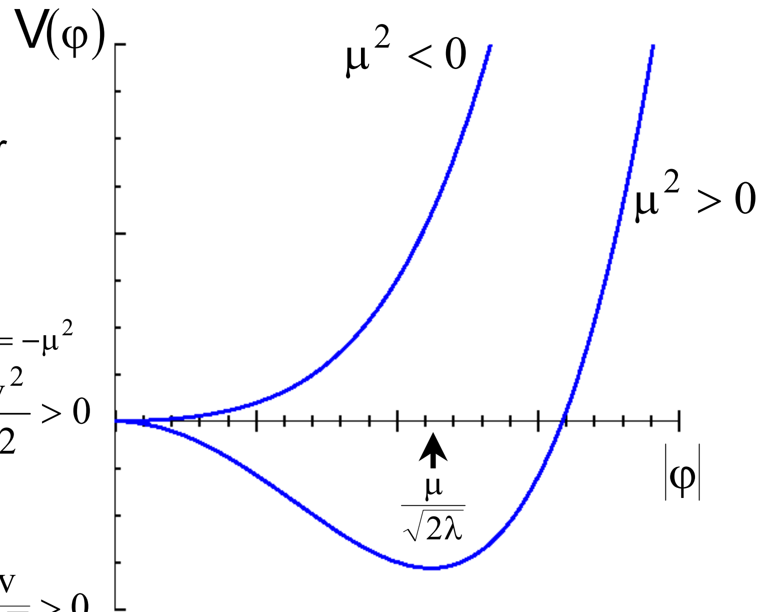
$$V(\varphi) = -\mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2 \qquad \lambda > 0$$

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

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

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



Theory: 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

$$\mathsf{L}=\tfrac{1}{2}\left(\partial_\mu\sigma\right)\left(\partial^\mu\sigma\right)-\mu^2\sigma^2+\tfrac{1}{2}\left(\partial_\mu\eta\right)\left(\partial^\mu\eta\right)+\mathsf{L}_{\mathrm{int}}$$

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

We can interpret ⟶

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

$\eta\rightarrow$ real Klein - Gordon field $m_\eta=0$ ⟶ Goldstone boson field

and ndf do add up ⟶

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

Theory: Higgs model

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

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

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

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

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

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

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

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

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

Theory: Higgs model (continued)

Obtain

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

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

but cannot interpret $\eta \rightarrow$ real Klein - Gordon field $m_\eta = 0$ ← aaarg!

$A^\mu \rightarrow$ real Proca field $M_A = q\text{v}$

and n.d.f would NOT add up

		n.d.f	
Initially:	complex φ	$\rightarrow$ 2	$\rightarrow$ 4
	real massless A^μ	$\rightarrow$ 2	
After :	real massive σ	$\rightarrow$ 1	$\rightarrow$ 5 !
	real massless η	$\rightarrow$ 1	
	real massive A^μ	$\rightarrow$ 3	

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

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

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

Theory: Higgs model (end)

In this gauge, we obtain

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

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

can interpret

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

$A^\mu \rightarrow$ real Proca field $\quad M_A = q\text{v}$

and n.d.f do add up →

		n.d.f	
Initially:	complex φ	$\rightarrow$ 2	$\rightarrow$ 4
	real massless A^μ	$\rightarrow$ 2	
After :	real massive σ	$\rightarrow$ 1	$\rightarrow$ 4
	real massive A^μ	$\rightarrow$ 3	

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 acquire mass without spoiling gauge invariance → Higgs mechanism

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

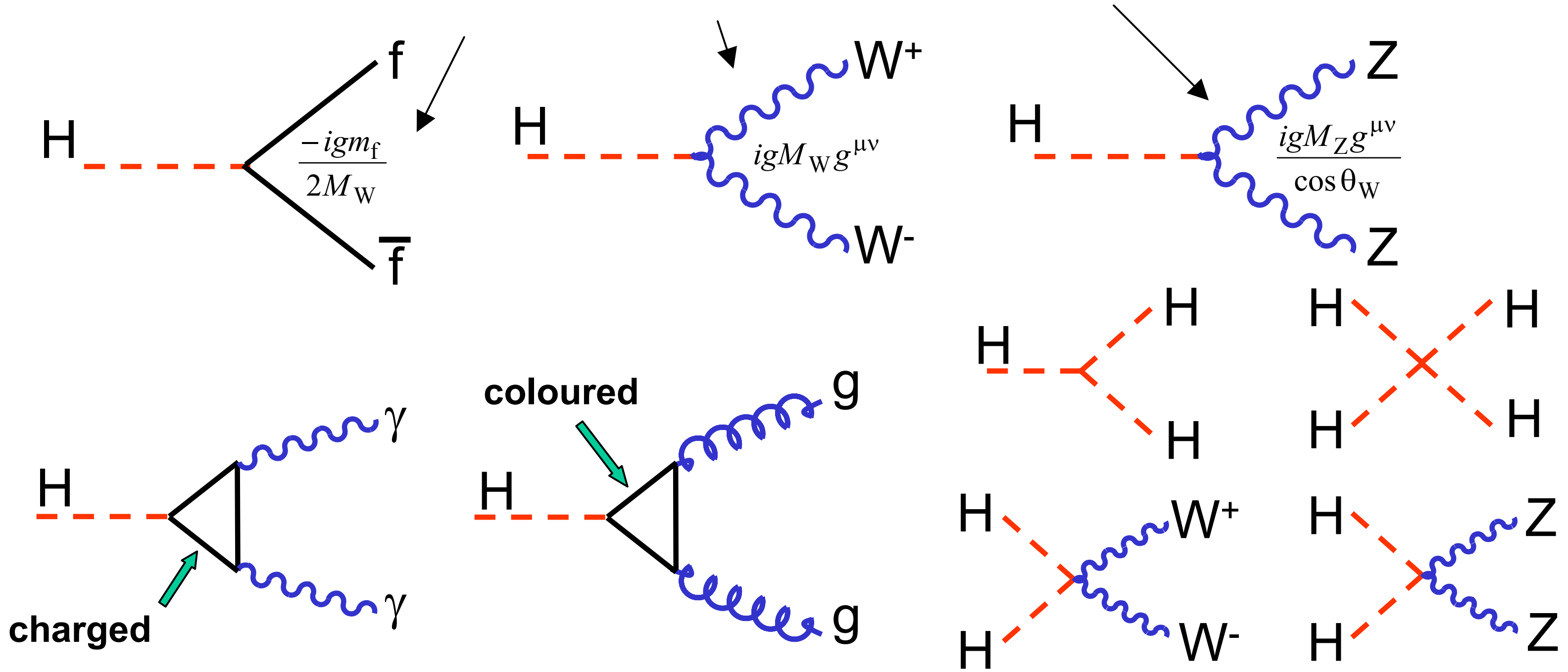
SM Higgs Interactions

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

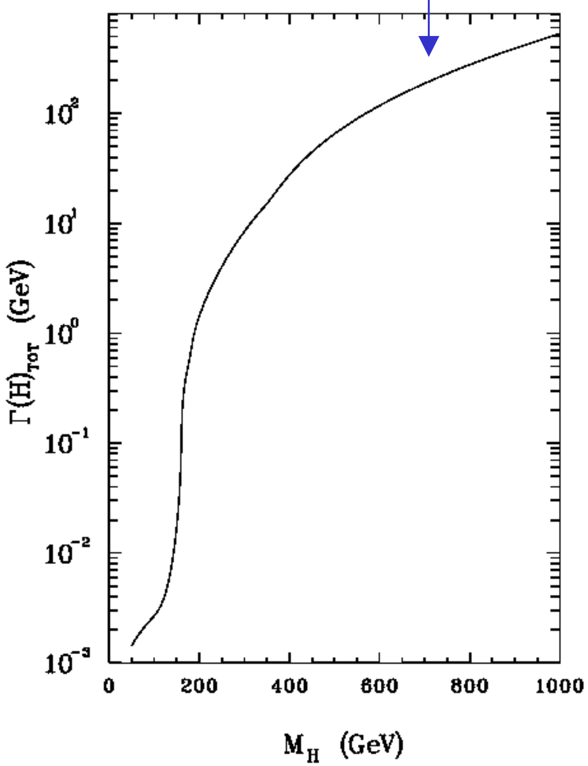
$\varphi(x)$ coupling with massless fermion fields ⟶ fermion masses

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

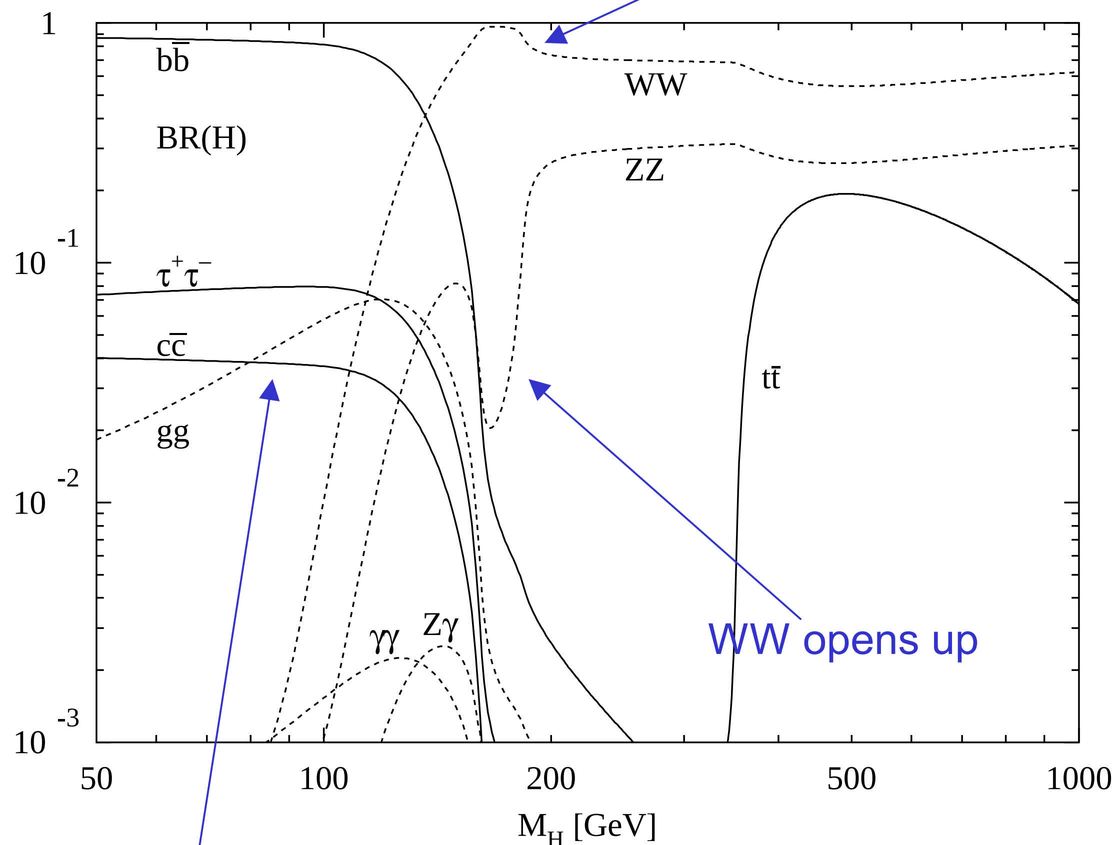


SM Higgs decays

Fat!



ZZ opens up

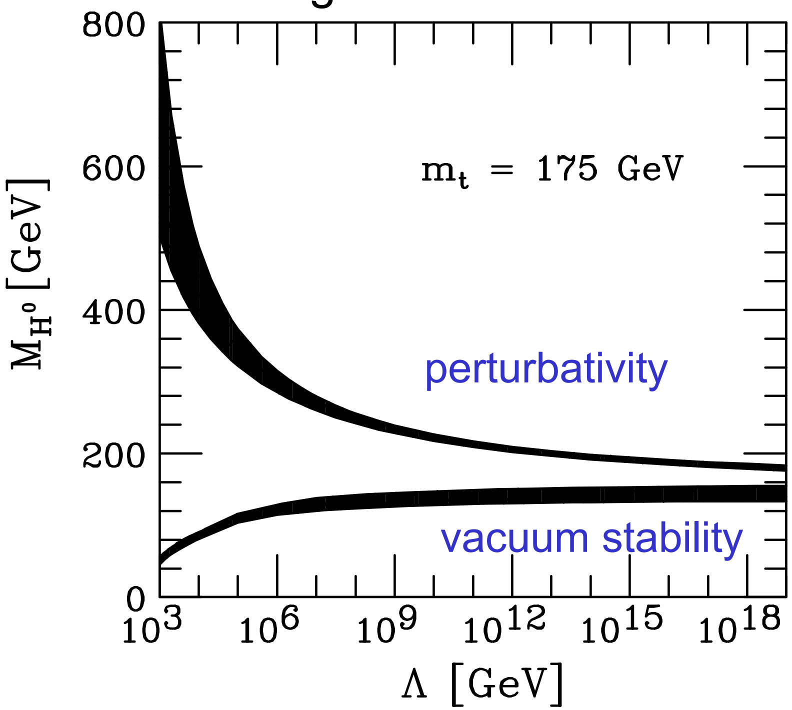


due to c reduced running mass

Theoretical constraints on M_H

M_H is a free parameter of SM

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

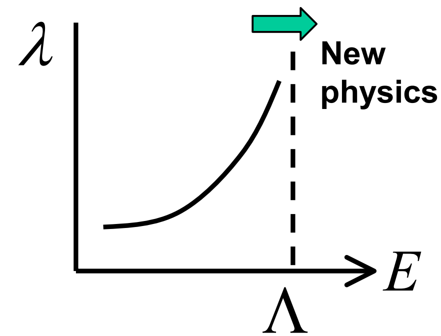


$$130\ \text{GeV} \approx< M_H \approx< 180\ \text{GeV}$$

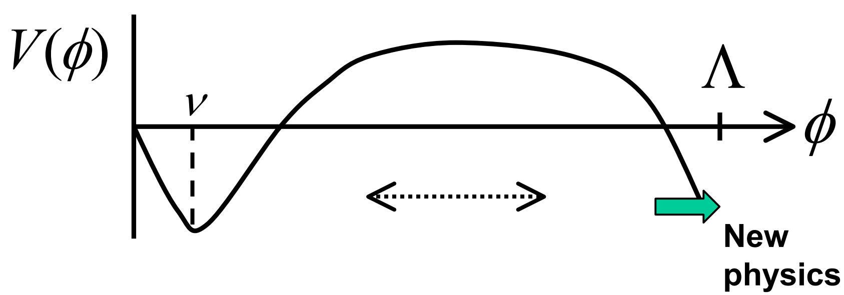
then, in principle consistent with $\Lambda = M_{PL}$

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

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

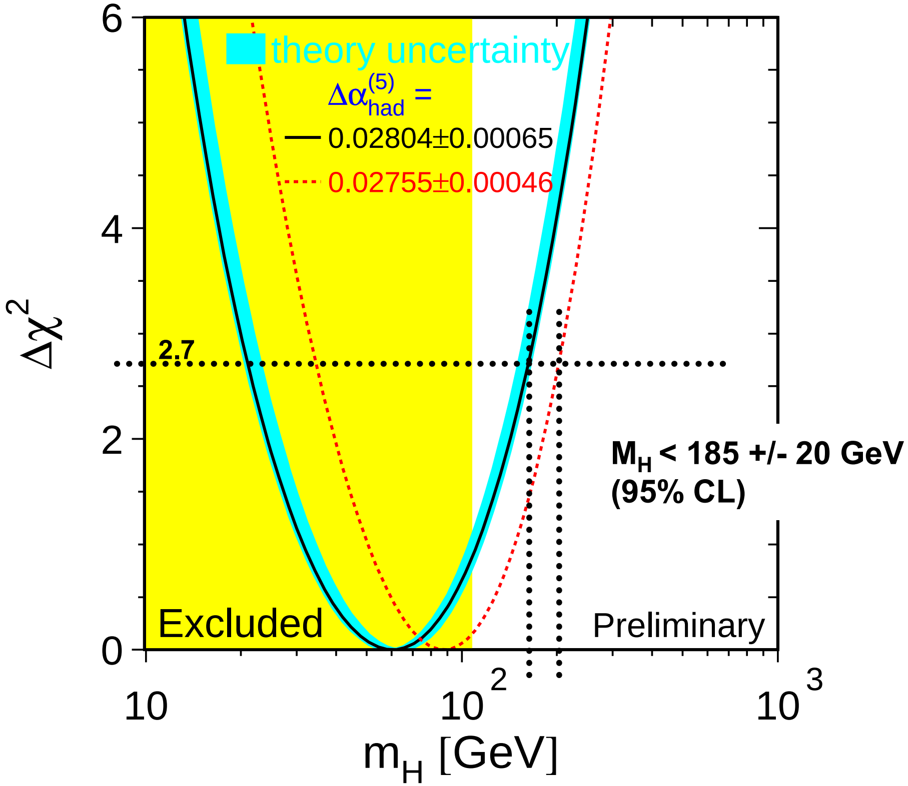


M_H is too small: the higgs potential develops a second (global!) minimum values of the scalar field of the order of Λ



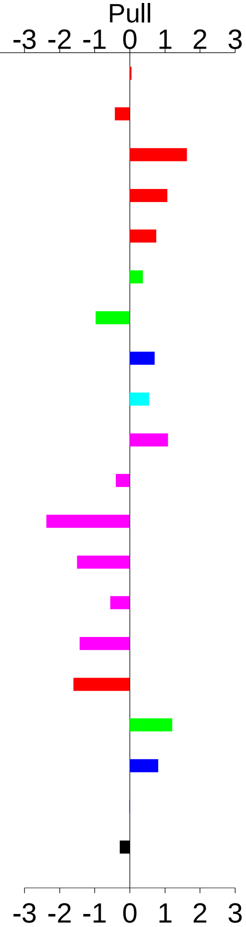
Experimental constraints on M_H

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

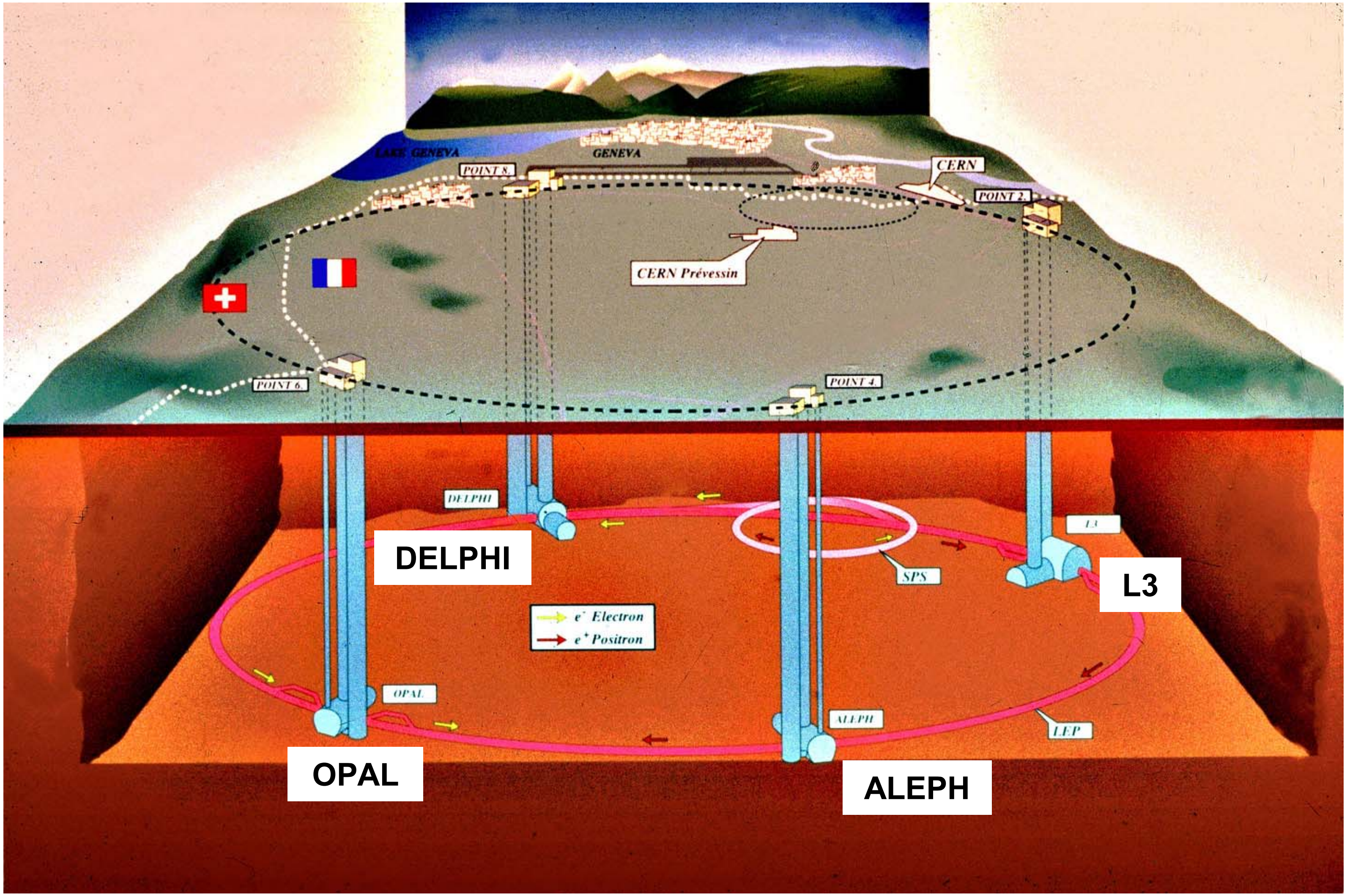


Osaka 2000

	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



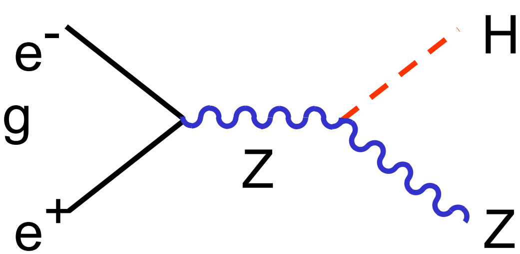
Large Electron Positron Collider



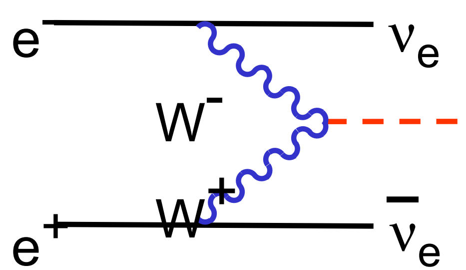
LEP data sets and SM Higgs production

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}

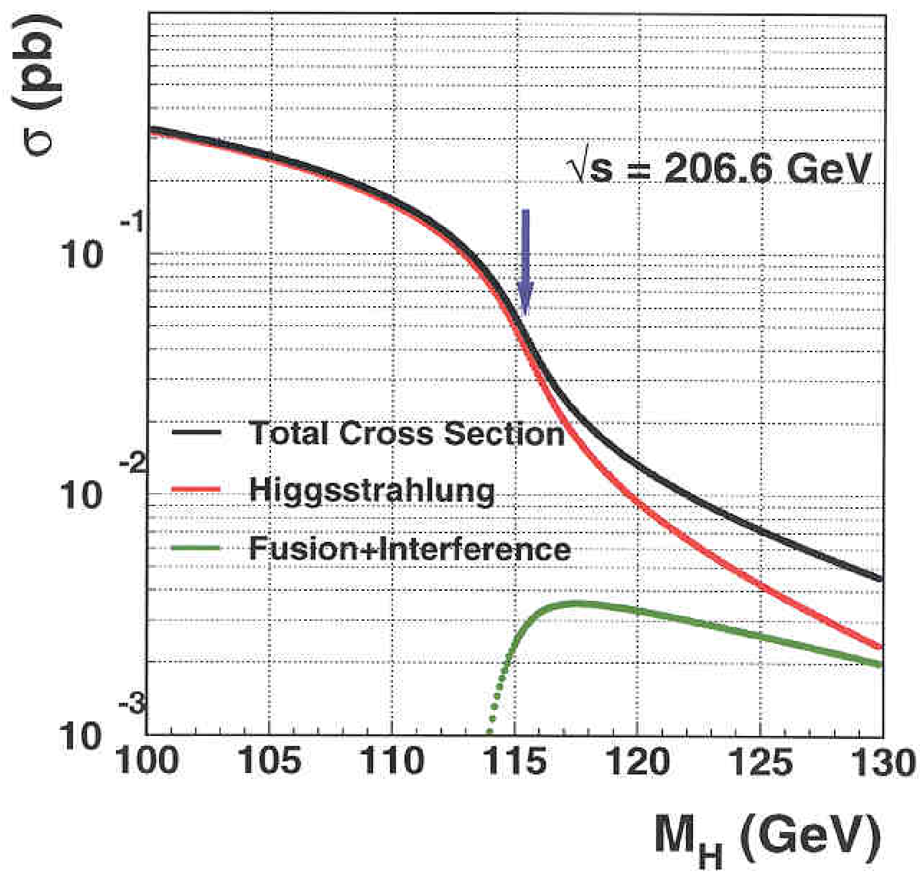
Higgsstrahlung



Fusion

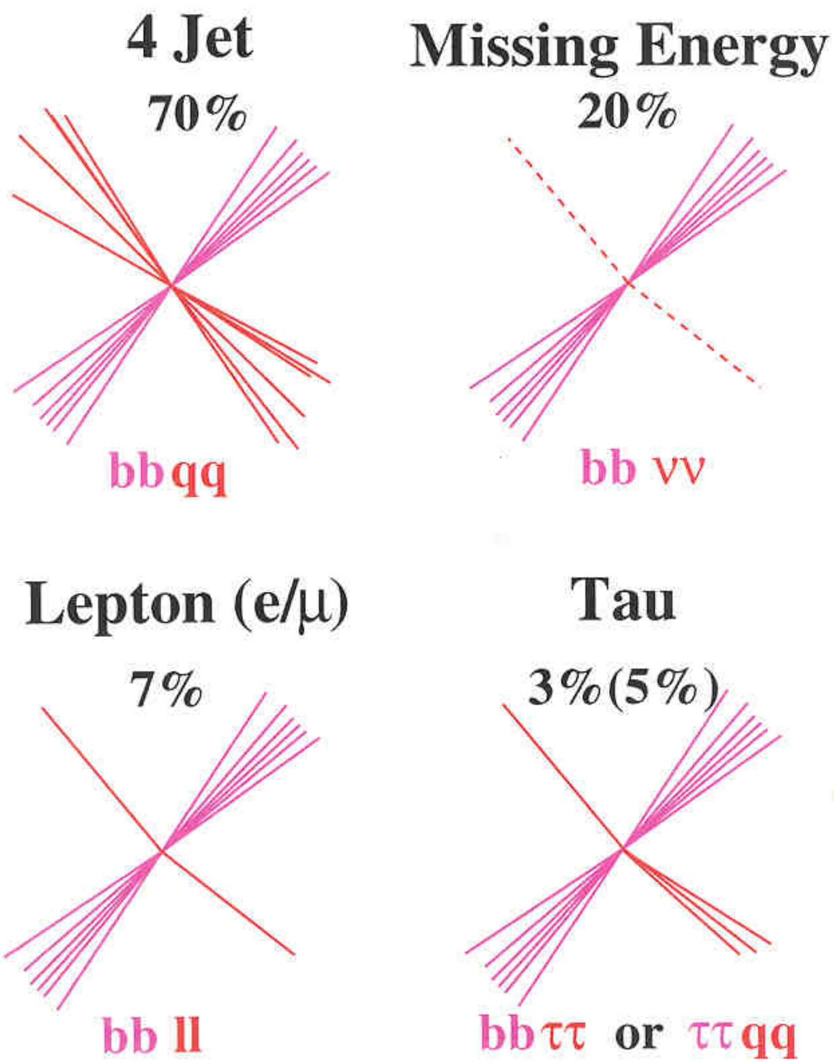


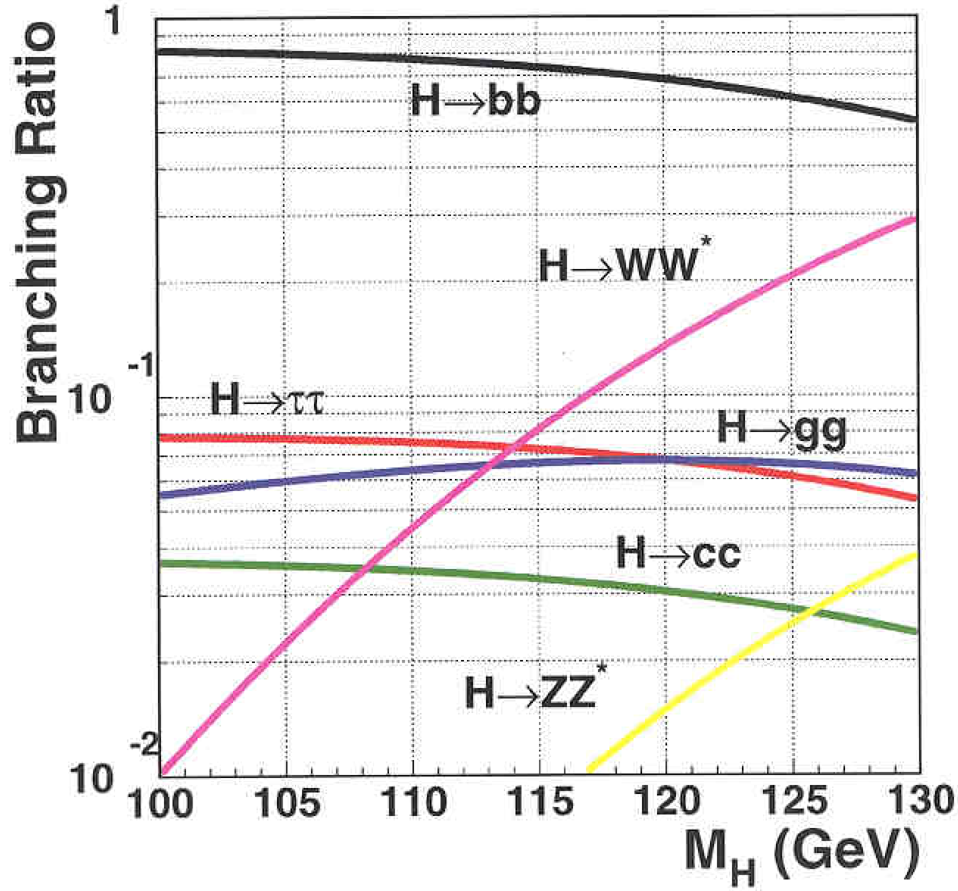
Rob McPherson



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

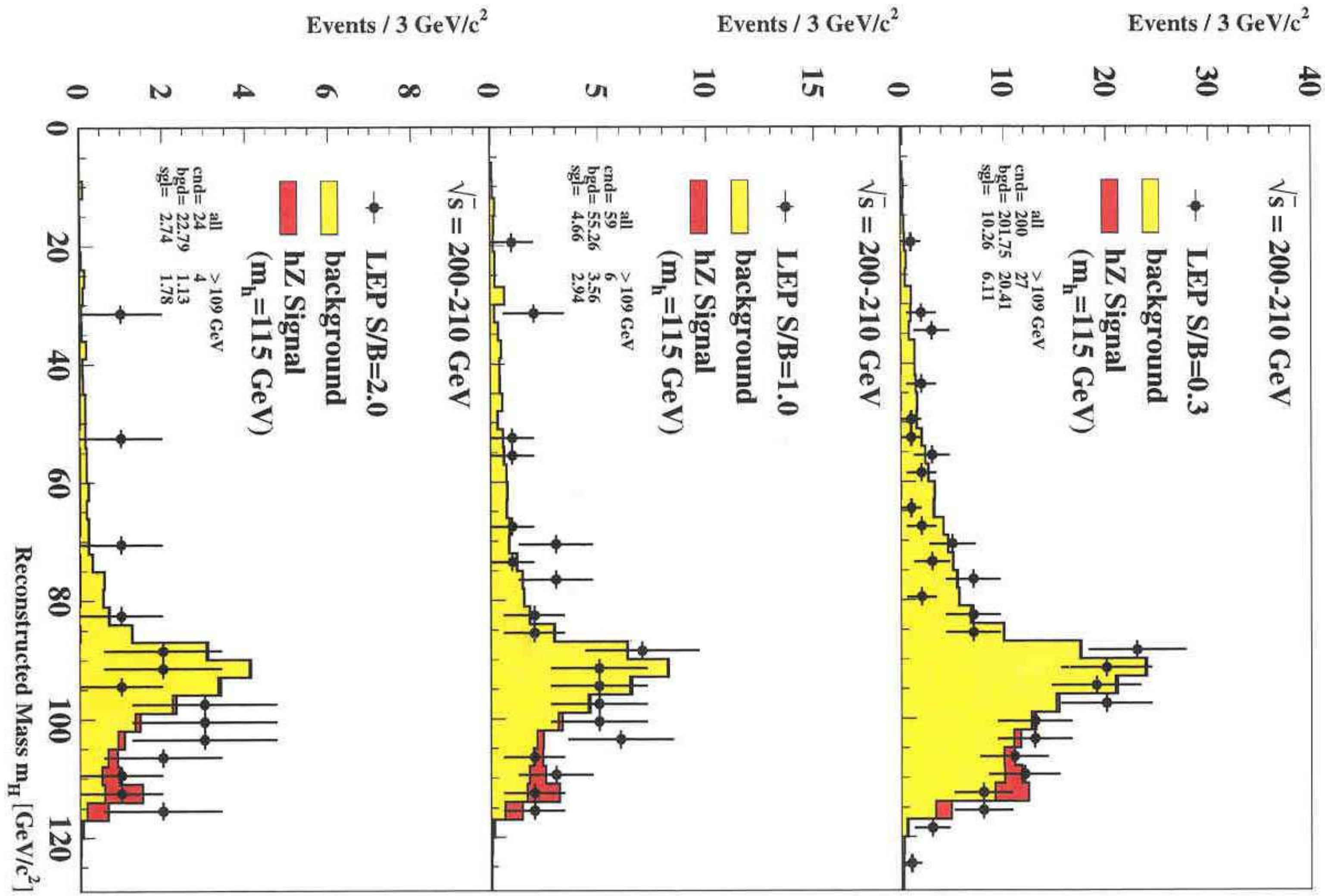
OPAL

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

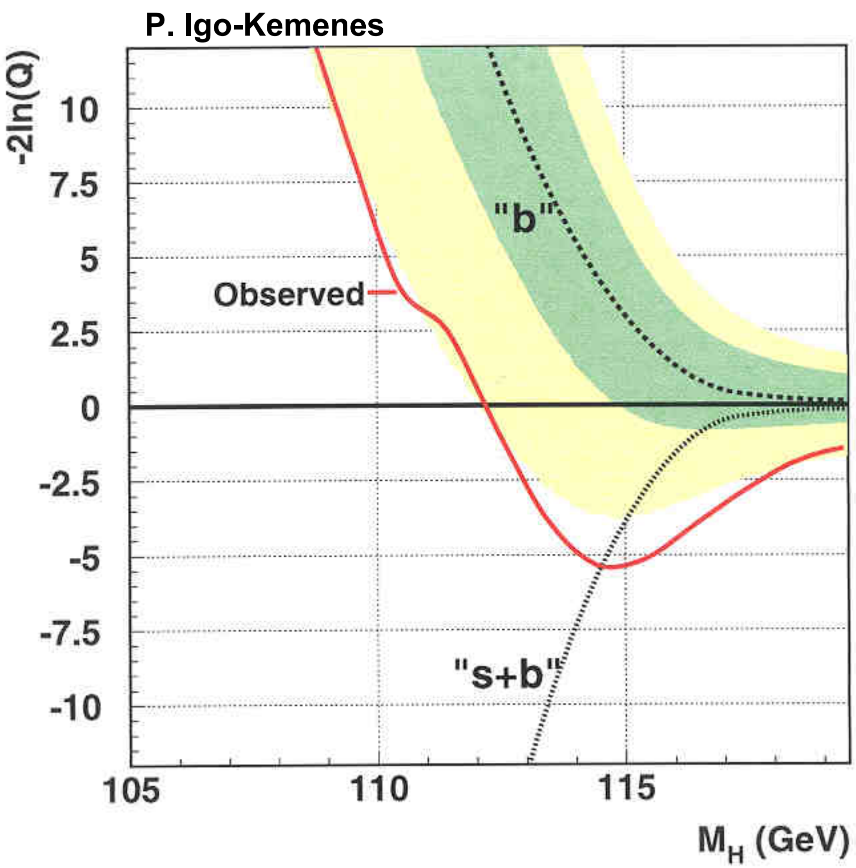
} i is a bin in $\left(M_{\mathrm{H}}^{\mathrm{rec}}, G\right)$ space for each channel

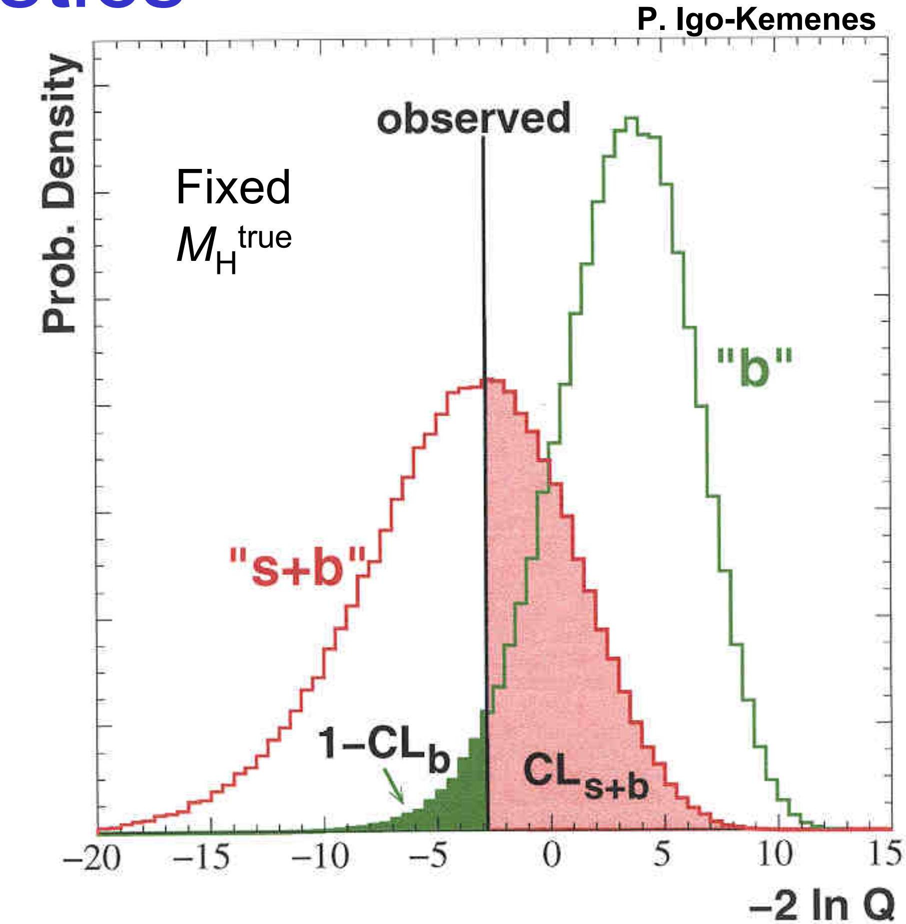
Likelihood $\mathrm{L}(x) = \prod_i \frac{\exp(-x_i)\, x_i^{N_i}}{N_i!}$

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





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

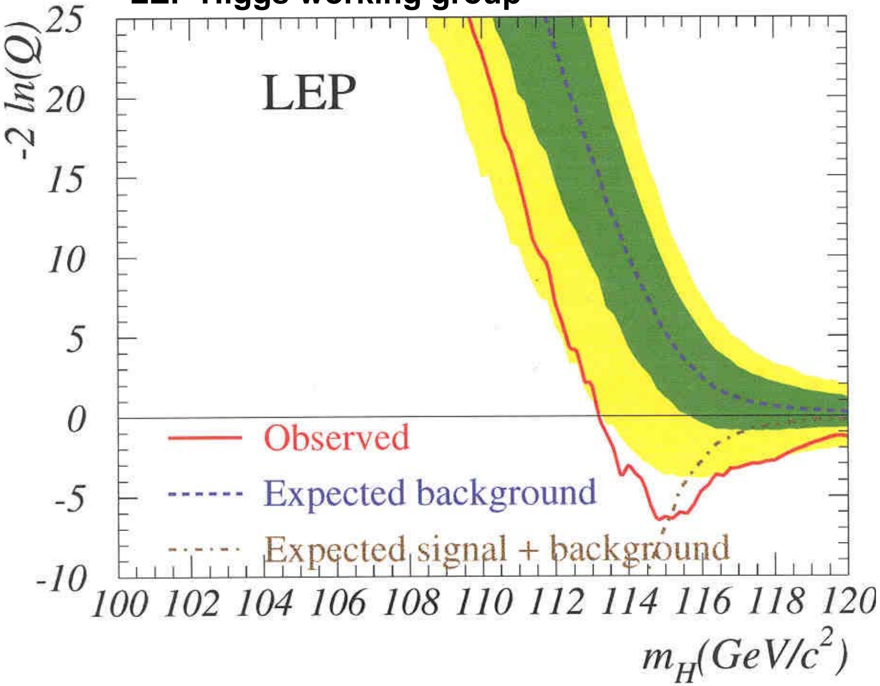
$1-CL_b$ measures compatibility with “b”

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

LEP Higgs working group



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

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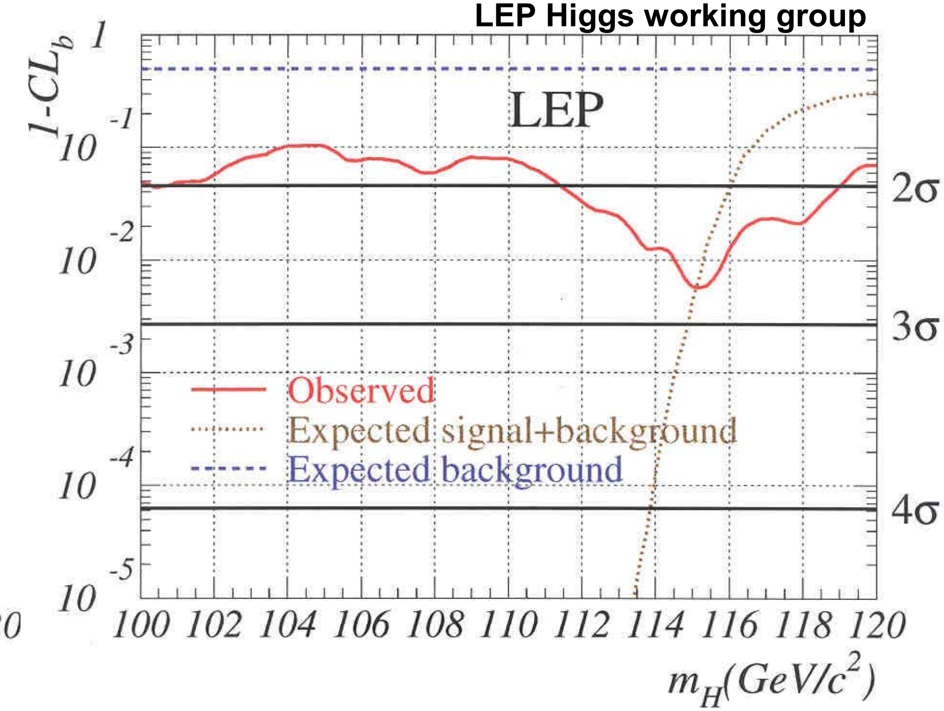
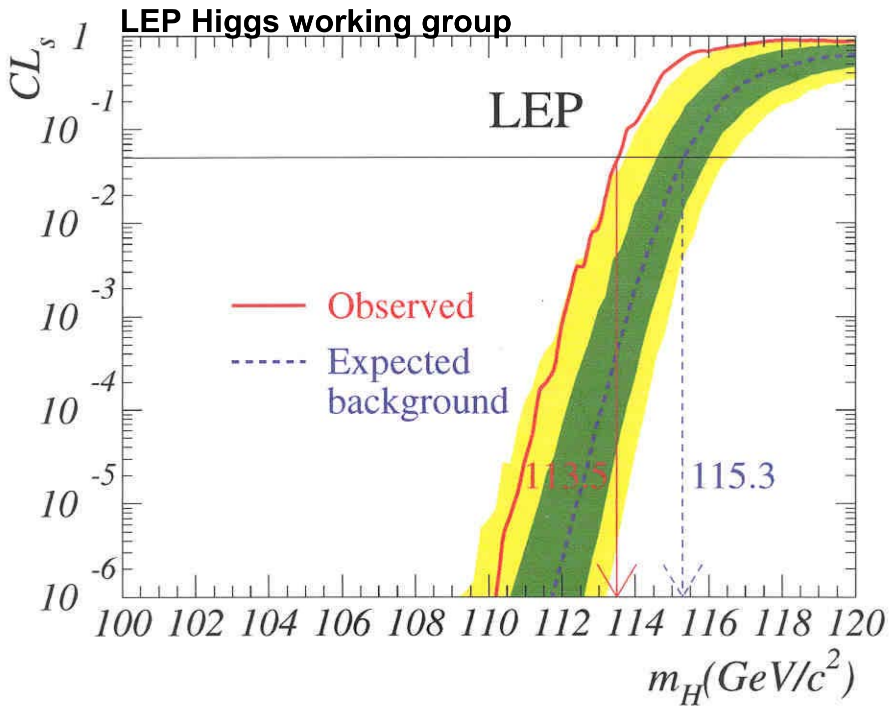


$$1 - CL_b = 2.9\sigma$$

Probability that what is observed is background is 0.4%

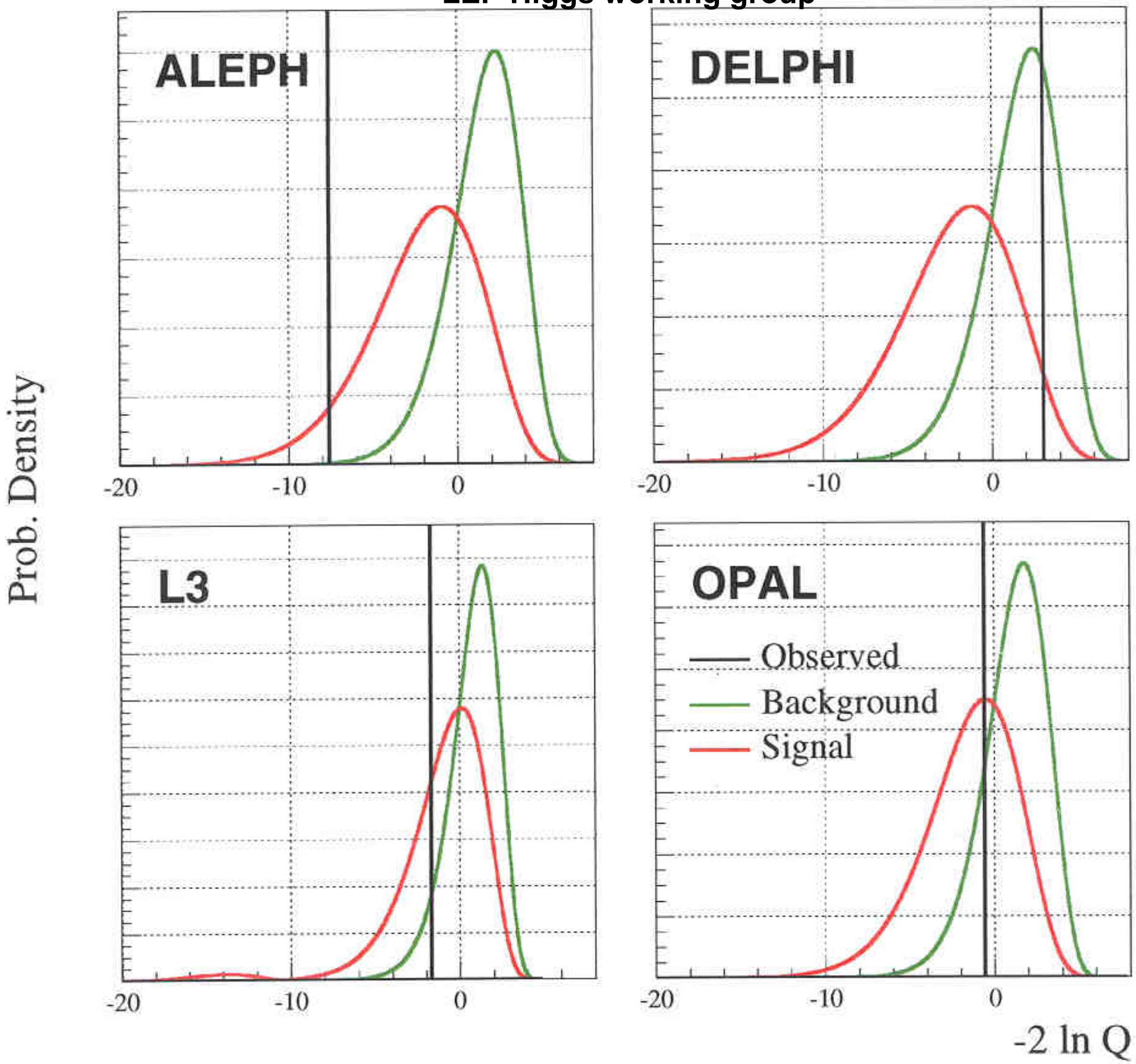
LEP SM Higgs lower bound



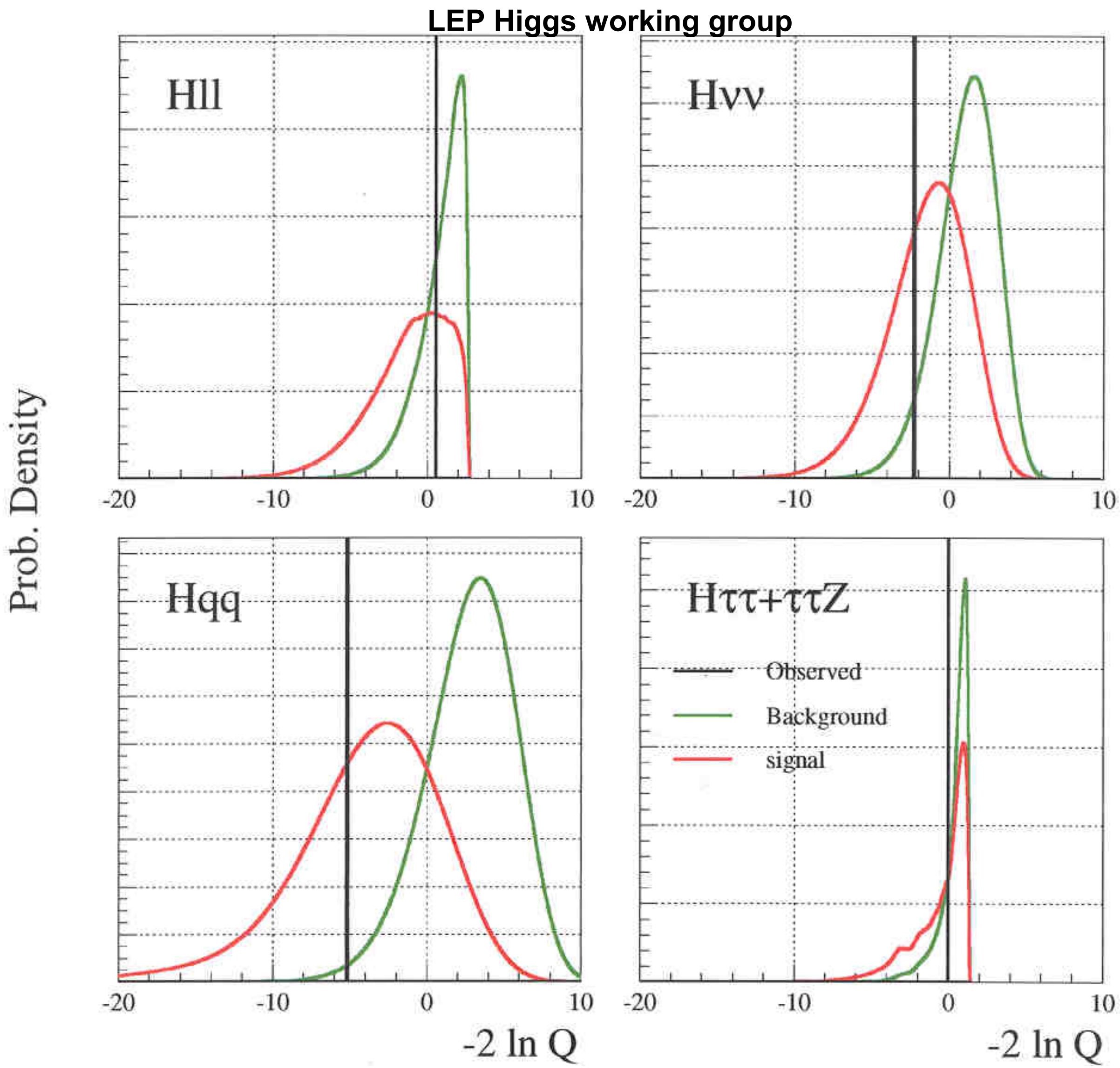
$$M_{\mathrm{H}} > 113.5\,\mathrm{GeV}\ @95\%\ \mathrm{CL}$$

Probability densities per detector

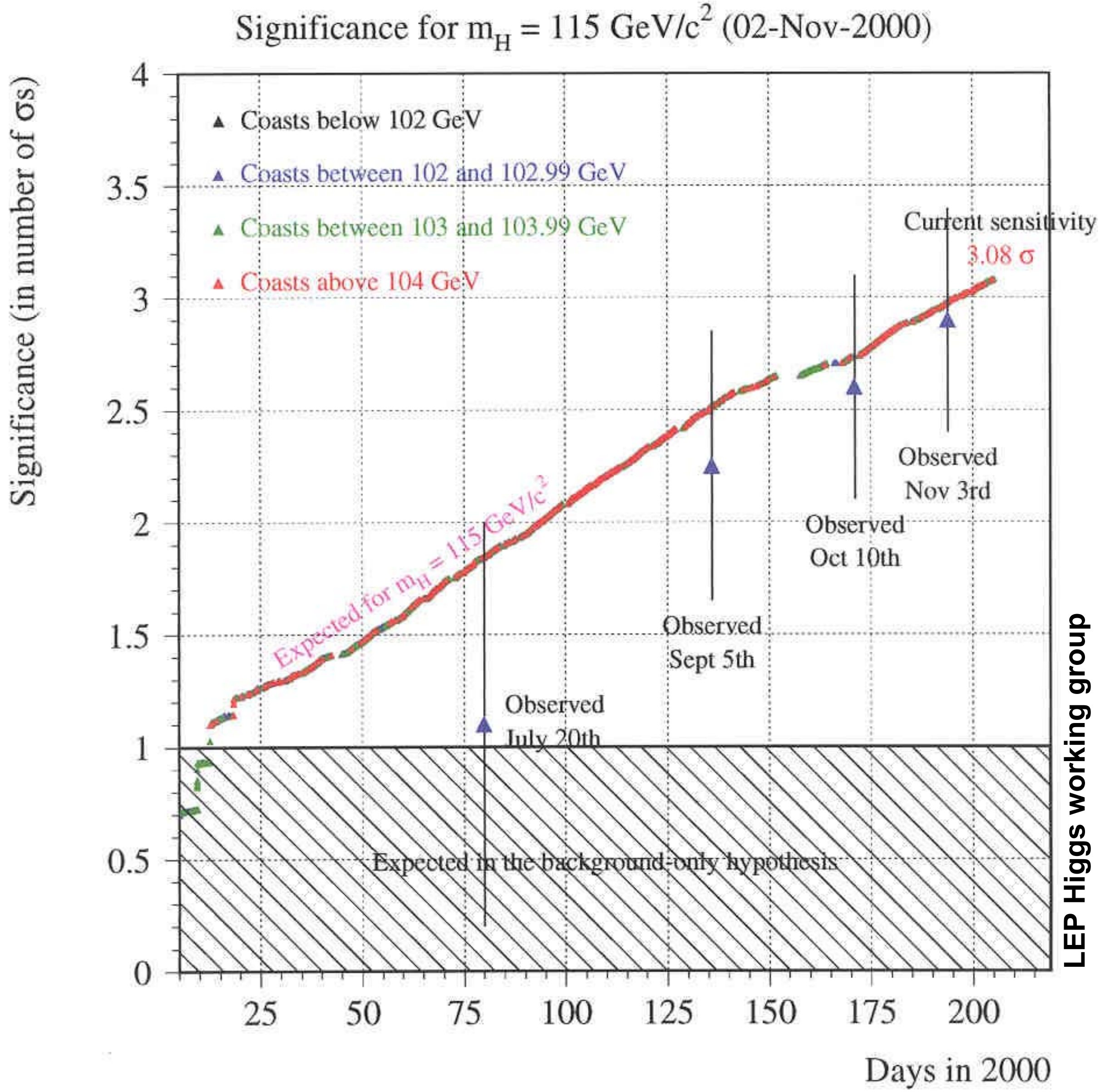
LEP Higgs working group



Probability densities per decay mode



Evolution with luminosity

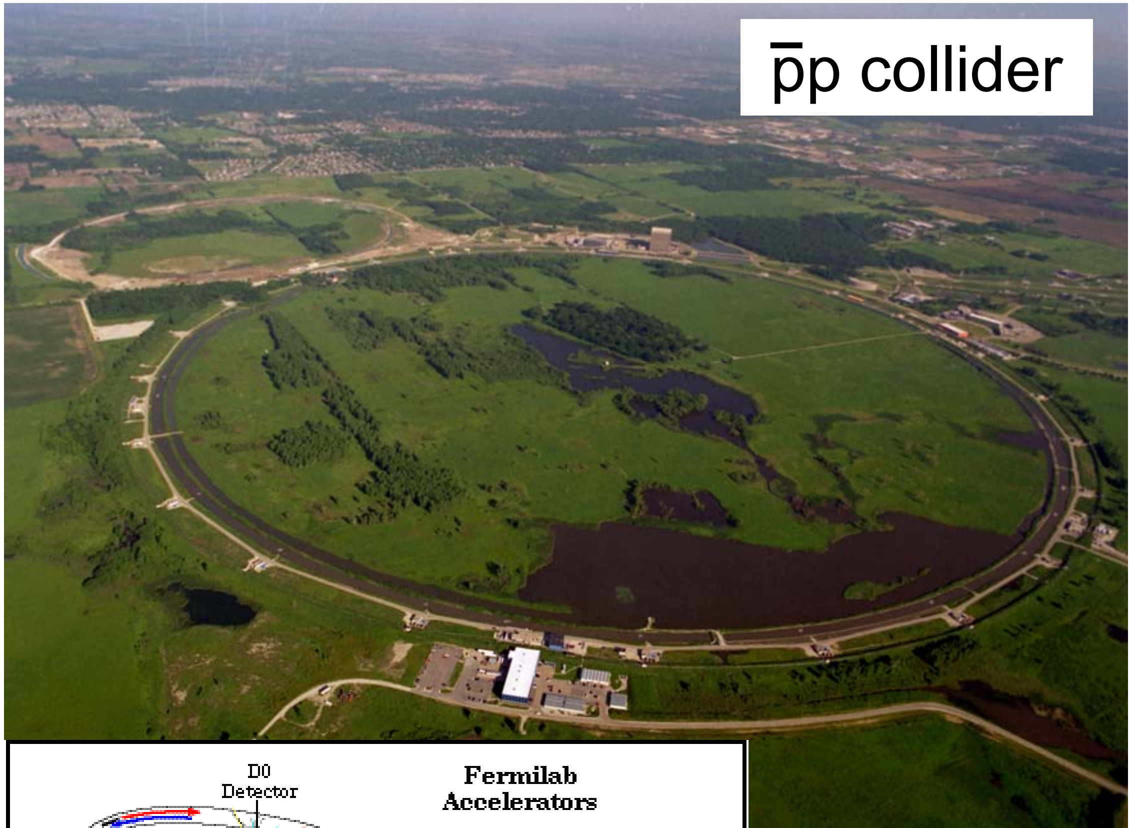


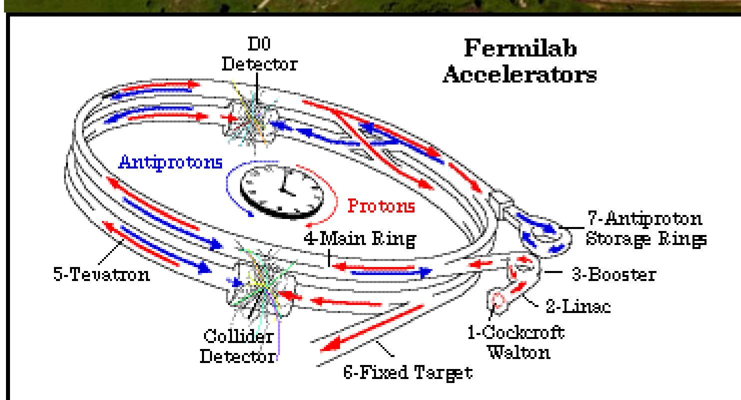
LEP community requested another 200 pb^{-1} in 2001 to reach 5σ

LEP is now being dismantled, to install the LHC

When will we know if LEP really detected a Higgs?

The Tevatron at Fermilab





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

- 6+6 bunches, 3.5 μs
- ≈1.6×10^{31} cm^{-2}s^{-1}
- ≈ 2 pb^{-1}week^{-1} per exp.

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

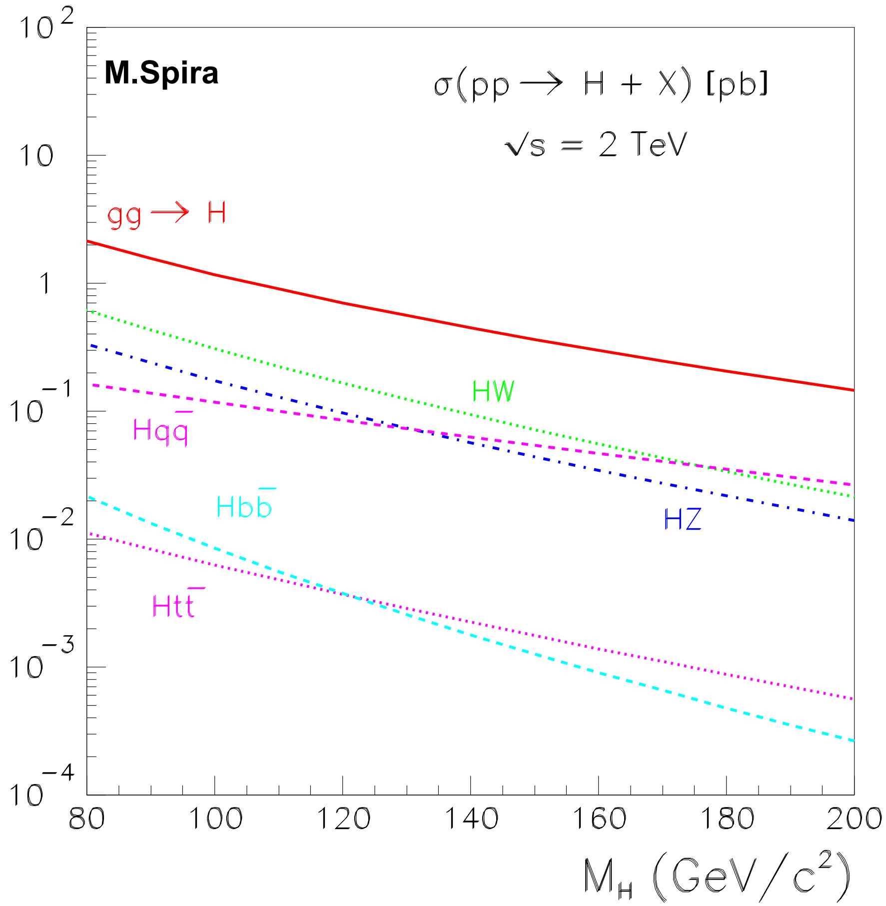
- 36+36 bunches, 396 ns
- start March 1st 2001
- goal, by end 2002
- ≈2×10^{32} cm^{-2}s^{-1}
- >2 fb^{-1}per exp.

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

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

hep-ph/0010338

SM Higgs production at the Tevatron



E. Barberis

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

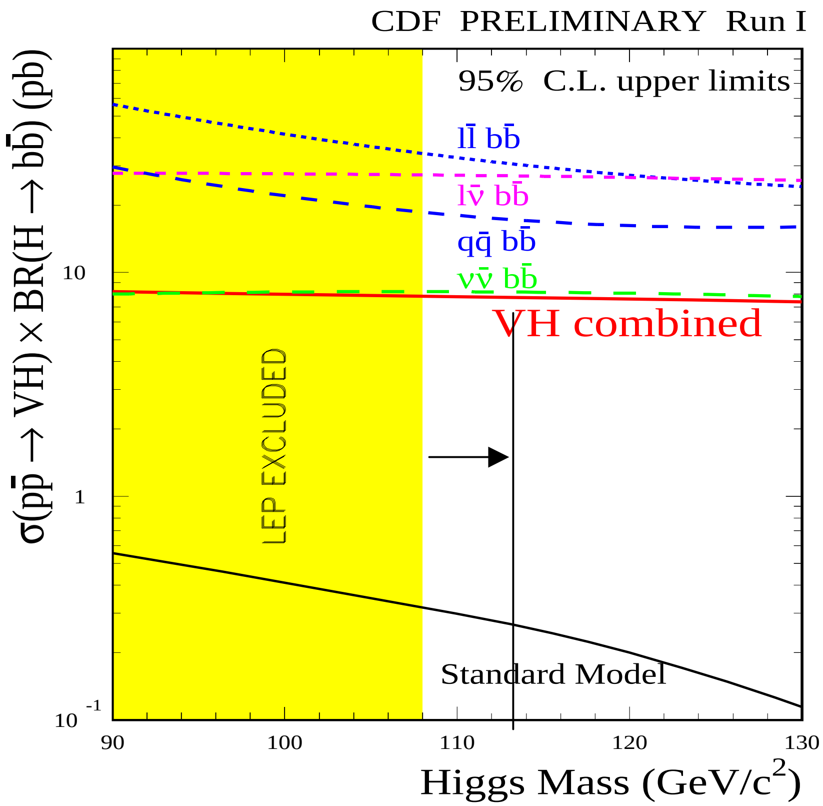
	σ[pb] (m_H=100 GeV)
$gg \rightarrow H$	1.0
WH	0.3
ZH	0.18
WZ	3.2
Wbb	11
tt	7.5
tb+tq+tbq	3.4
QCD	$O(10^6)$

WH/ZH production are preferred

SM Higgs searches at the Tevatron

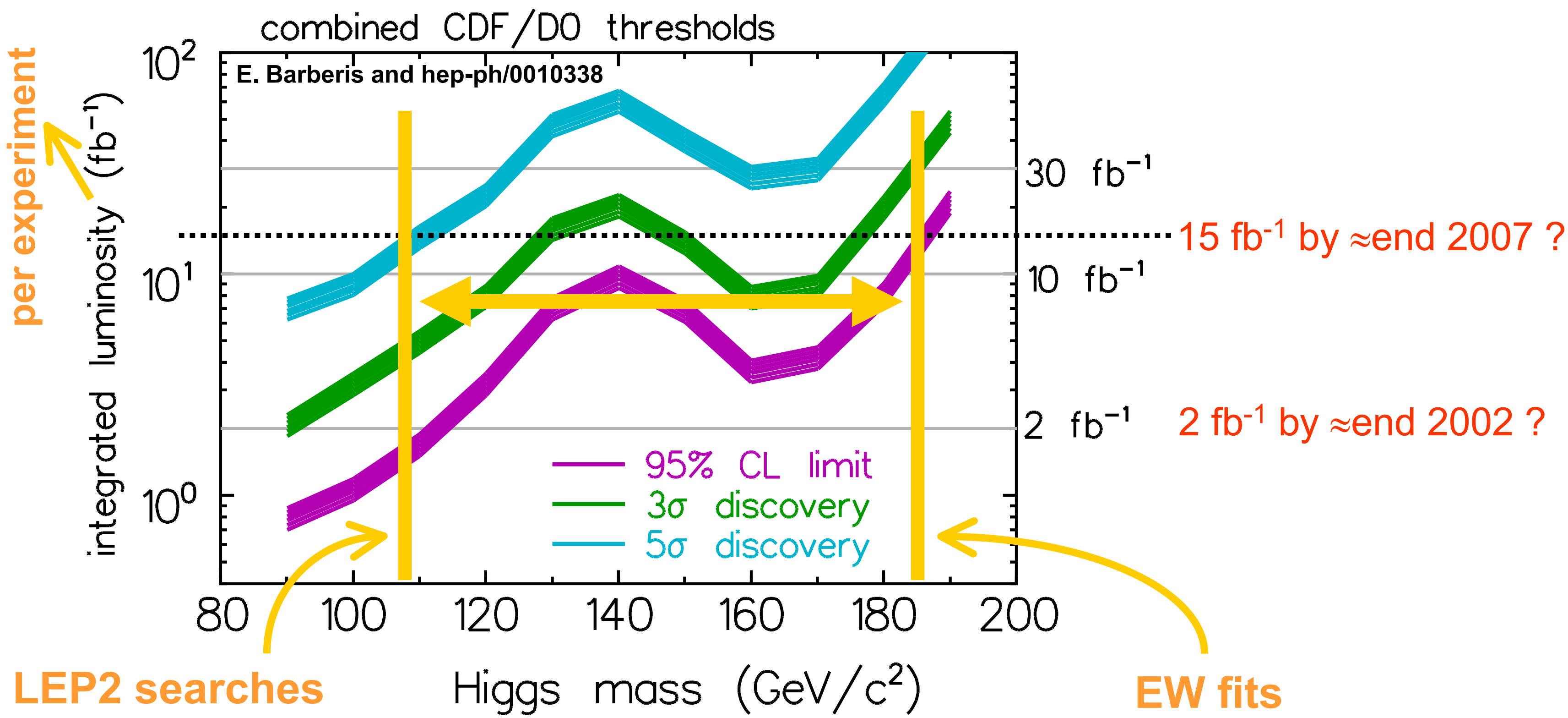
CDF: SVX b-tagging

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



one order of magnitude away from prediction

SM Higgs discovery at the Tevatron



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

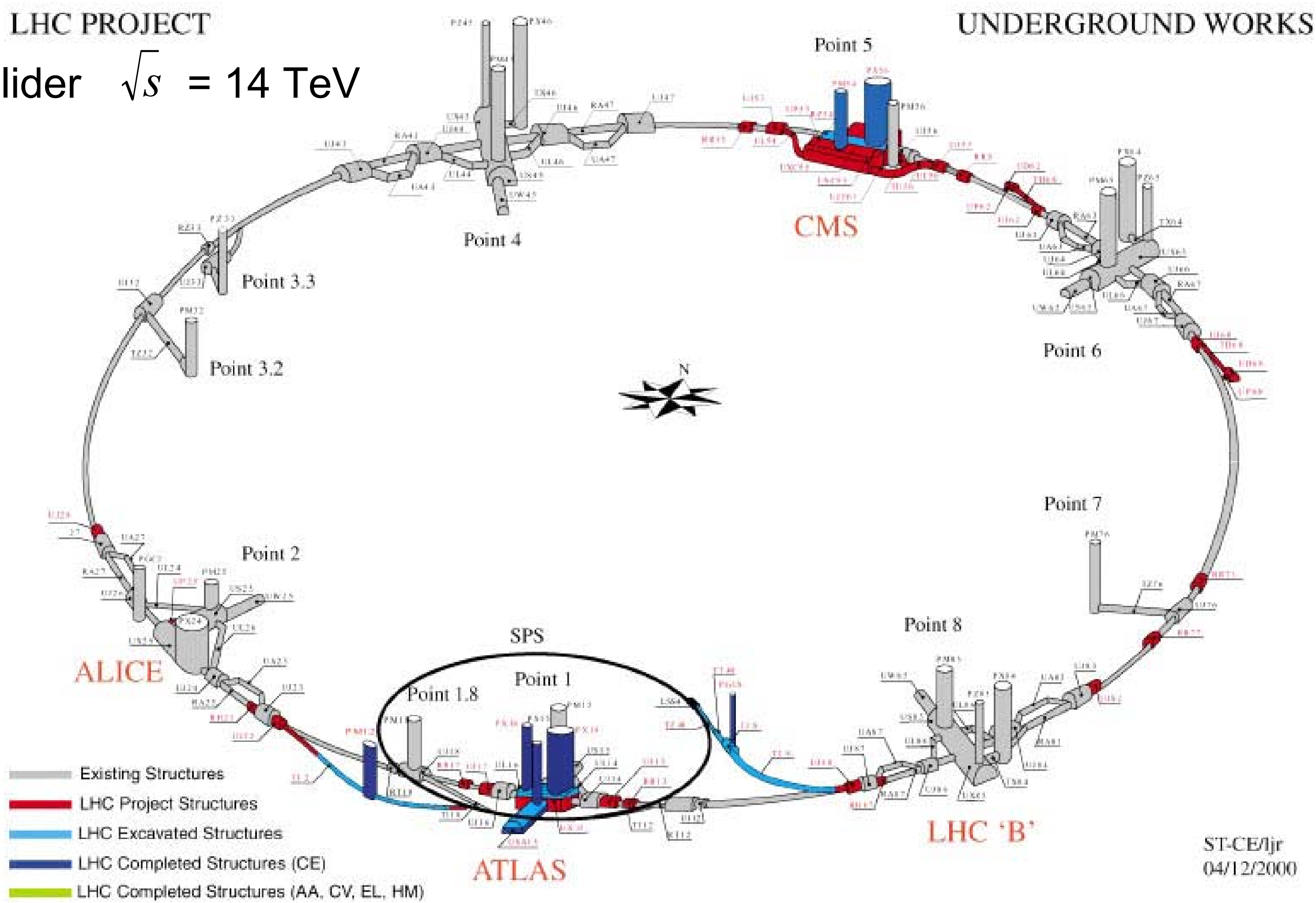
10 fb^{-1} **95% CL exclusion to M_H≈180 GeV in the absence of signal**

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

Aerial view of CERN

Large Hadron Collider at CERN

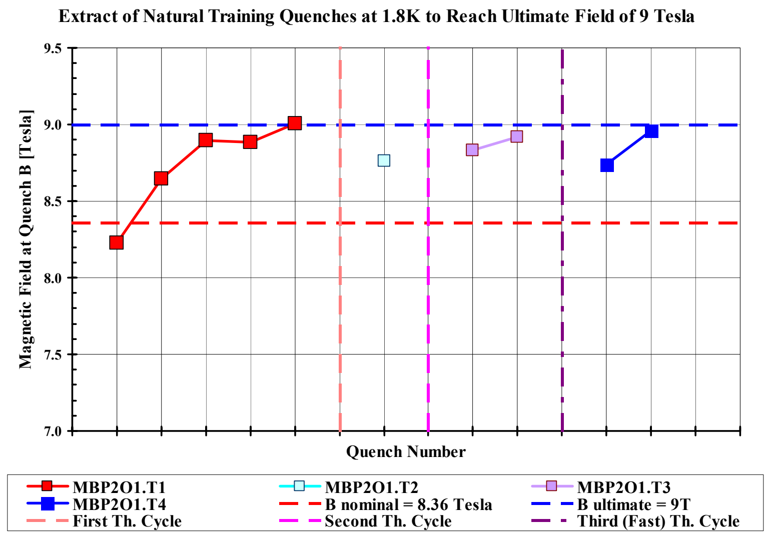
pp collider $\sqrt{s}$ = 14 TeV



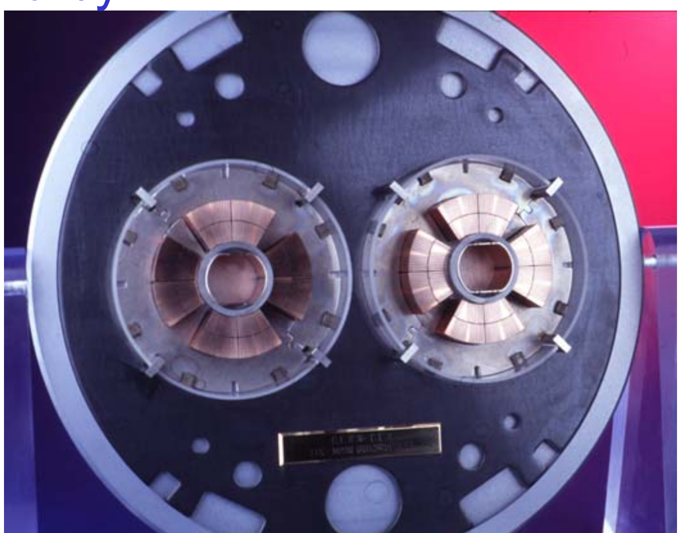
Large Hadron Collider at CERN

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

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



ATLAS pit
3/11/2000

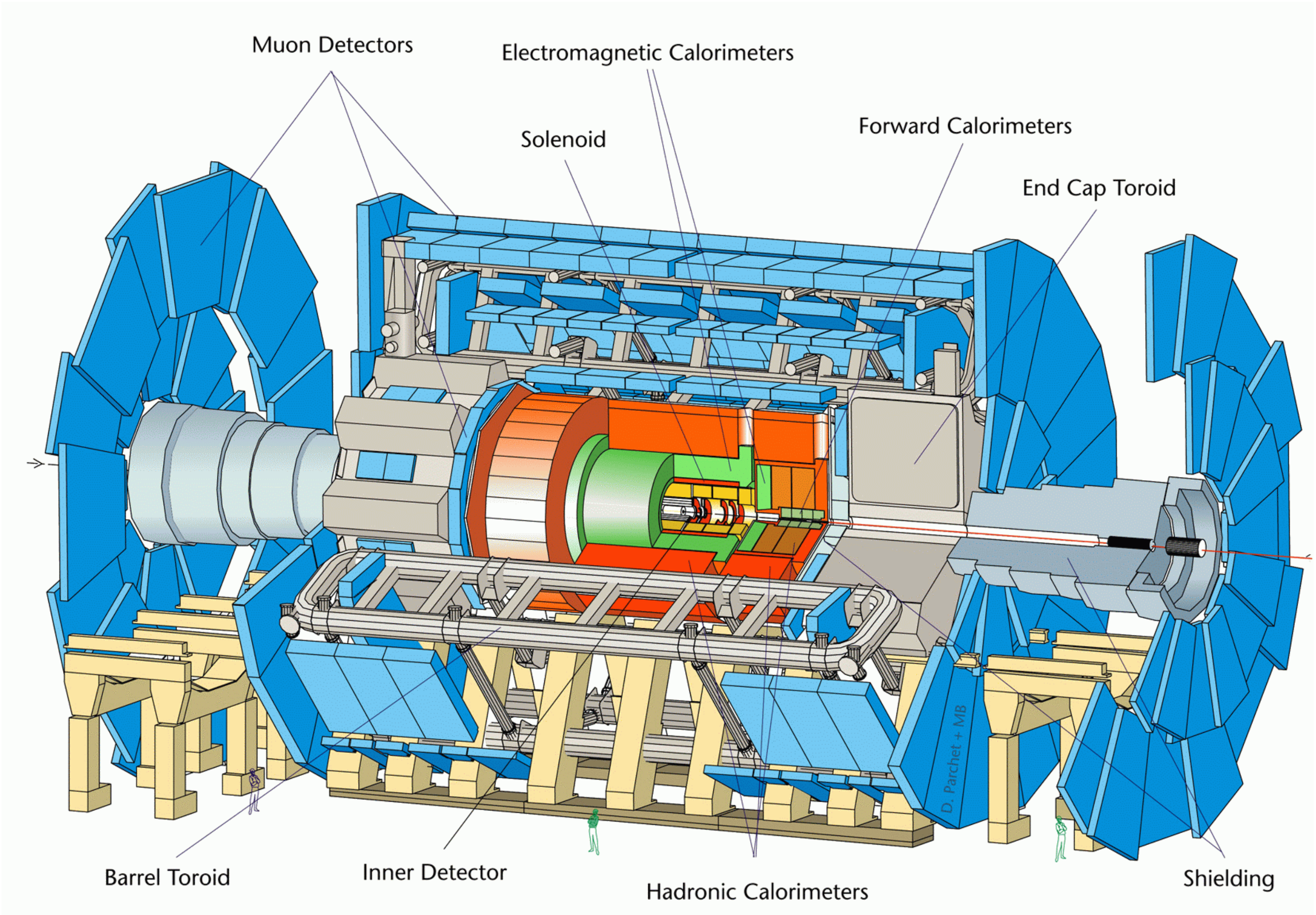


5000 superconducting magnets (1296 dipoles)
Cu-clad Nb-Ti cables to operate at 1.9K with up to 15kA

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

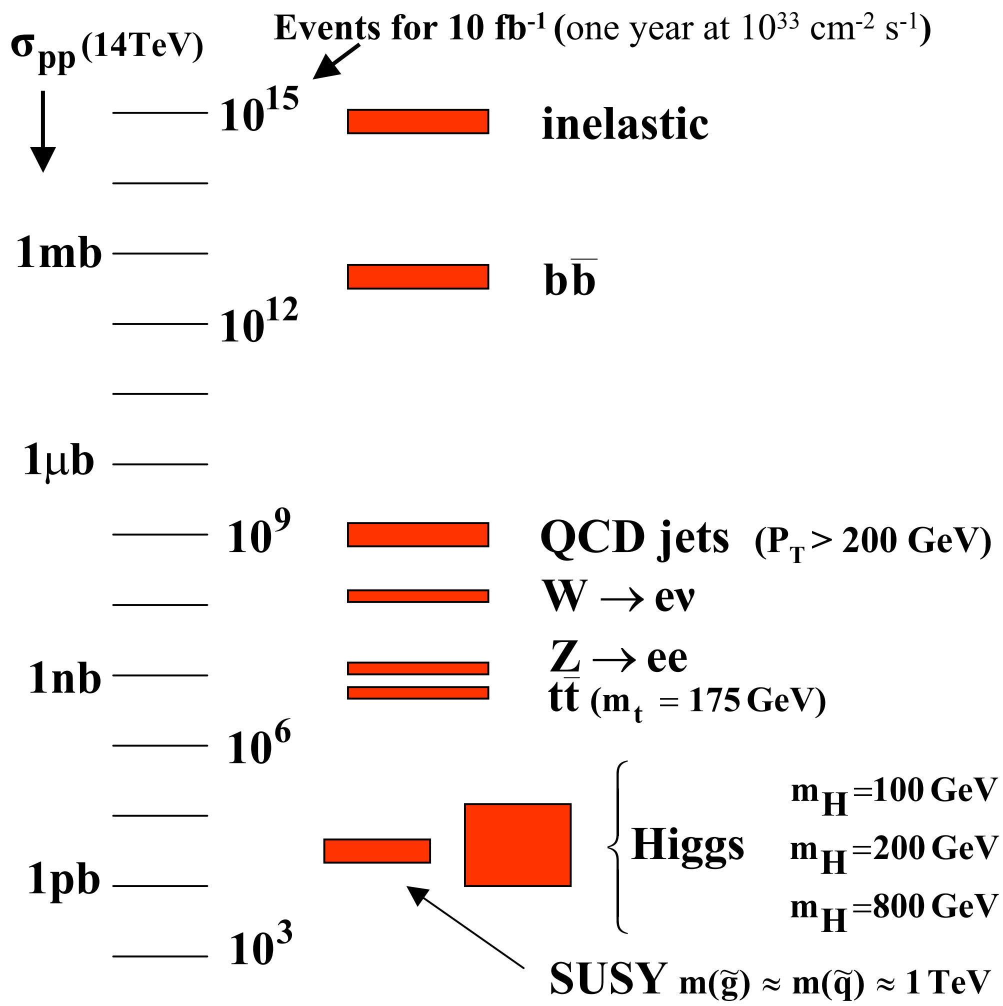
LHC: 25×E and 10k×L of SPS for same power

The ATLAS Detector

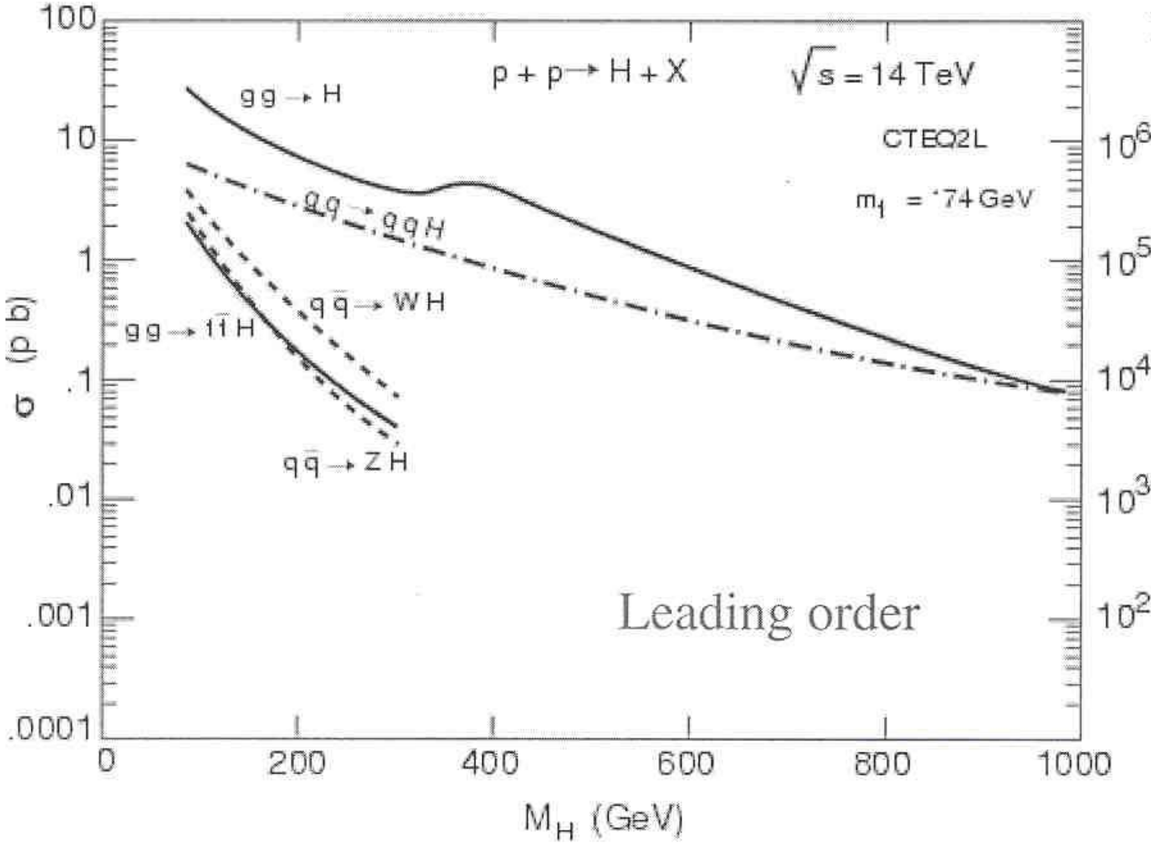


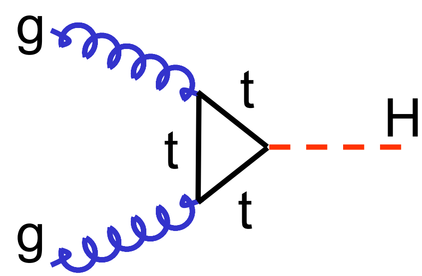
Alberta
Carleton
CRPP
Montréal
Toronto
TRIUMF
UBC
Victoria
York

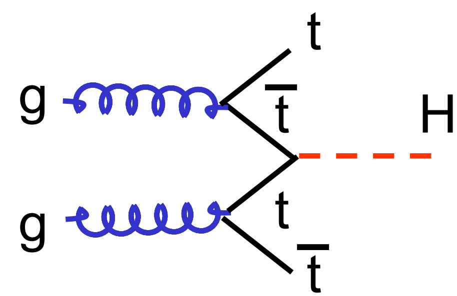
LHC PP cross section

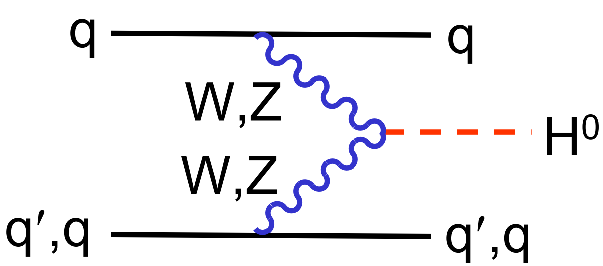


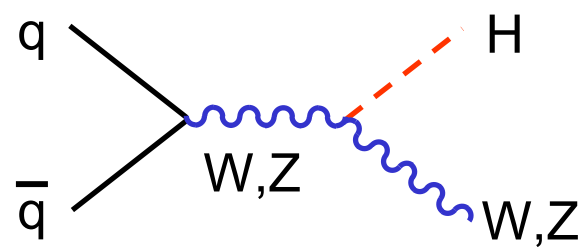
SM Higgs production at the LHC











Main SM Higgs search channels

Large QCD backgrounds:

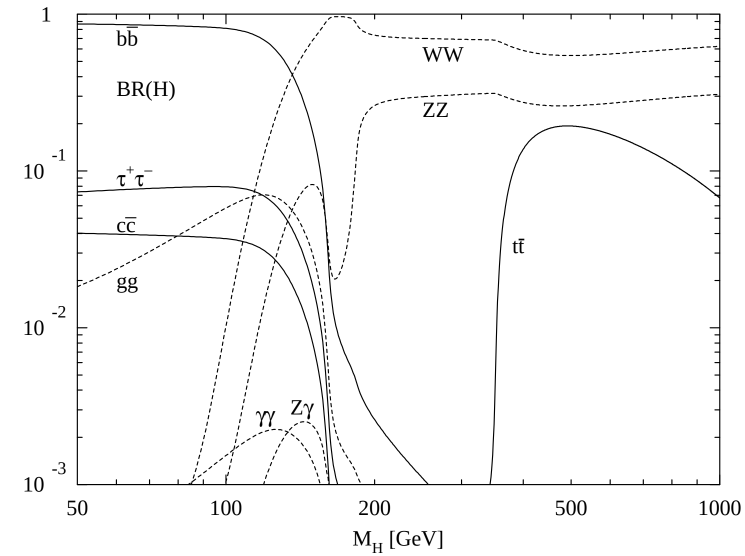
$$\sigma\left(H \to b\bar{b}\right) \approx 20\ \text{pb}$$
$$\sigma\left(b\bar{b}\right) \approx 500\ \mu\text{b}$$

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**
- $H \to ZZ^* \to 4l$
- $H \to WW^* \to l\,\nu\, l\,\nu$

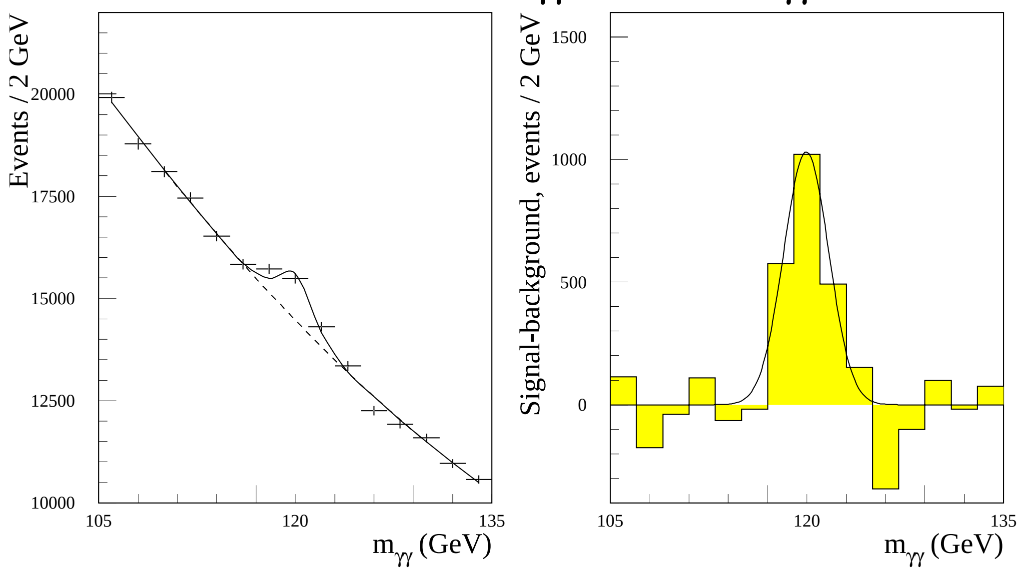
$M_H > 2M_Z$

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

(last three:) **M_H > 300 GeV forward jet tag**

$H \to \gamma\gamma$ at ATLAS

Signal	$\sigma \times BR = 43\ fb\ (m_H = 100\ GeV)$
$\gamma\gamma$ background (irreducible)	$\frac{d\sigma}{dm_{\gamma\gamma}} \sim 1200\ fb/GeV\ (m_{\gamma\gamma} = 100\ GeV)$
QCD jet background	$\frac{\sigma_{\gamma,j}}{\sigma_{\gamma\gamma}} \sim 1000, \quad \frac{\sigma_{j,j}}{\sigma_{\gamma\gamma}} \sim 2 \times 10^6$ **(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

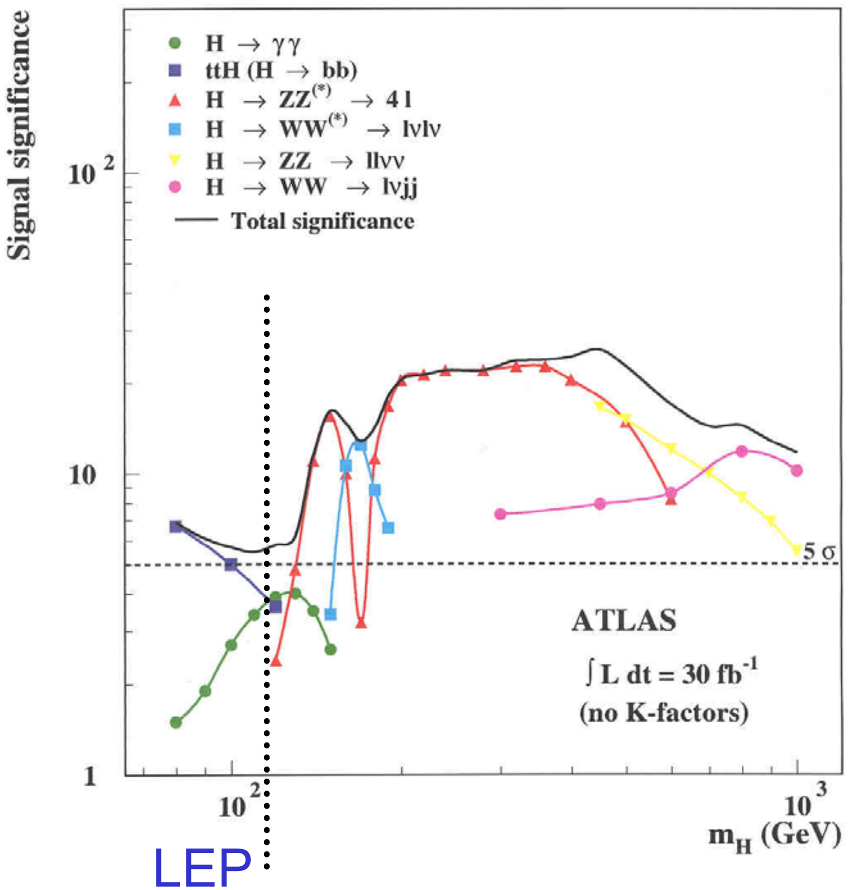
Analysis:

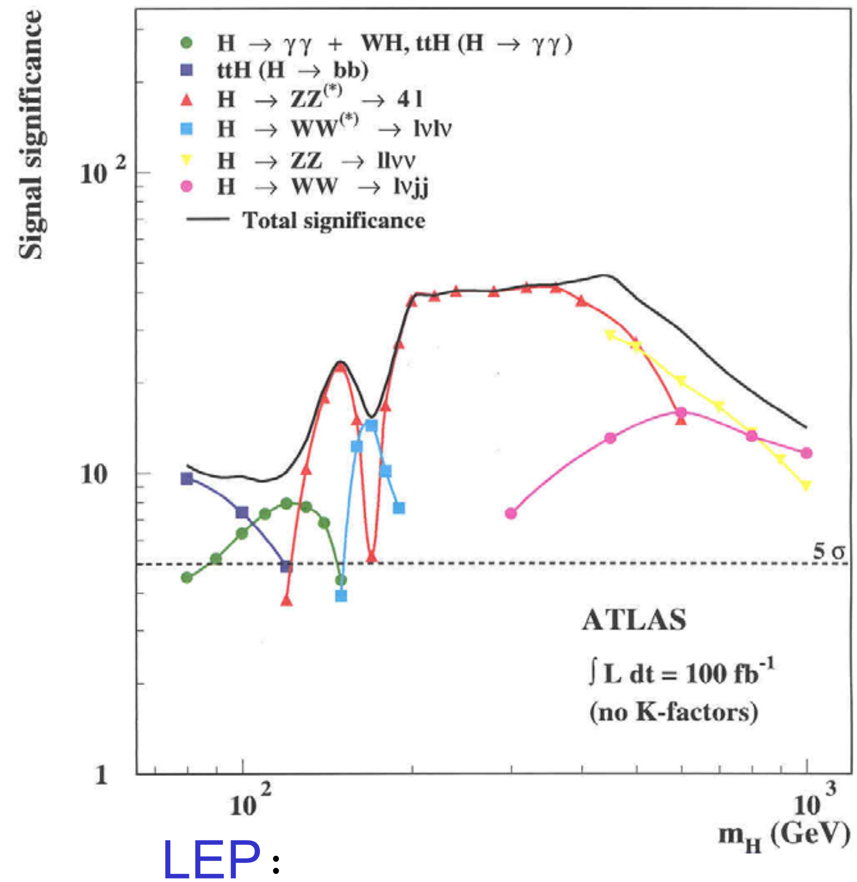
Two isolated γ's: p_T^1>40 GeV, p_T^2>25 GeV, $|\eta|$<2.5

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

Good mass resolution: σ_m=1.3 GeV for m_H=100 GeV

ATLAS SM Higgs discovery potential



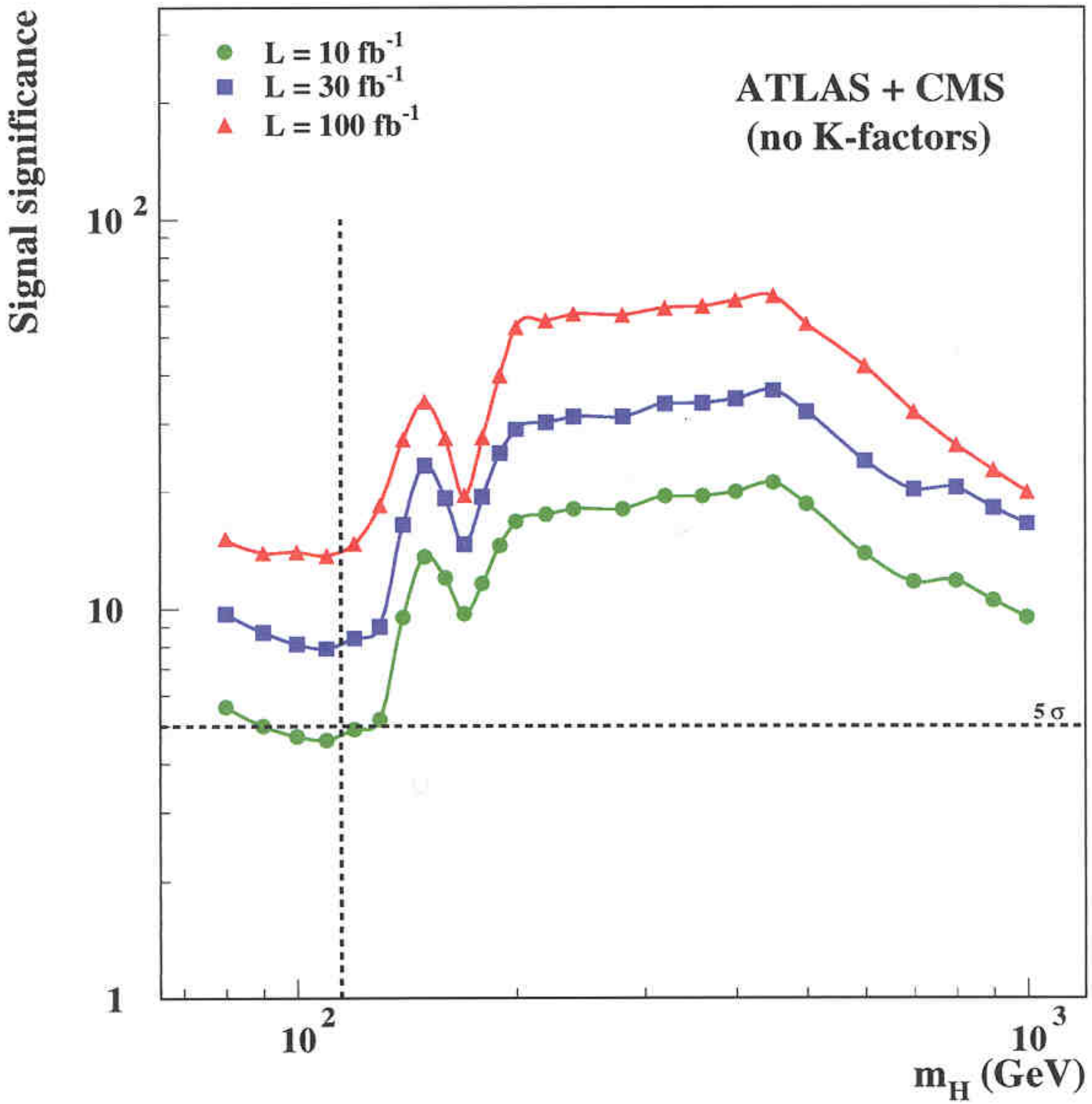


SM Higgs can be discovered over full mass range with 30 fb^{-1}

In most cases, more than one channel is available.

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

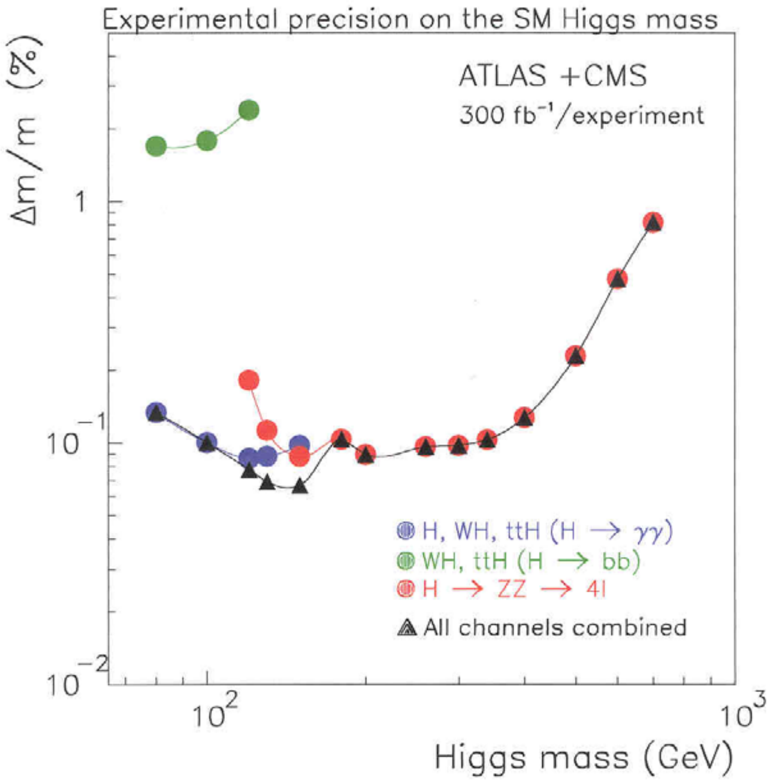
LHC SM Higgs discovery potential

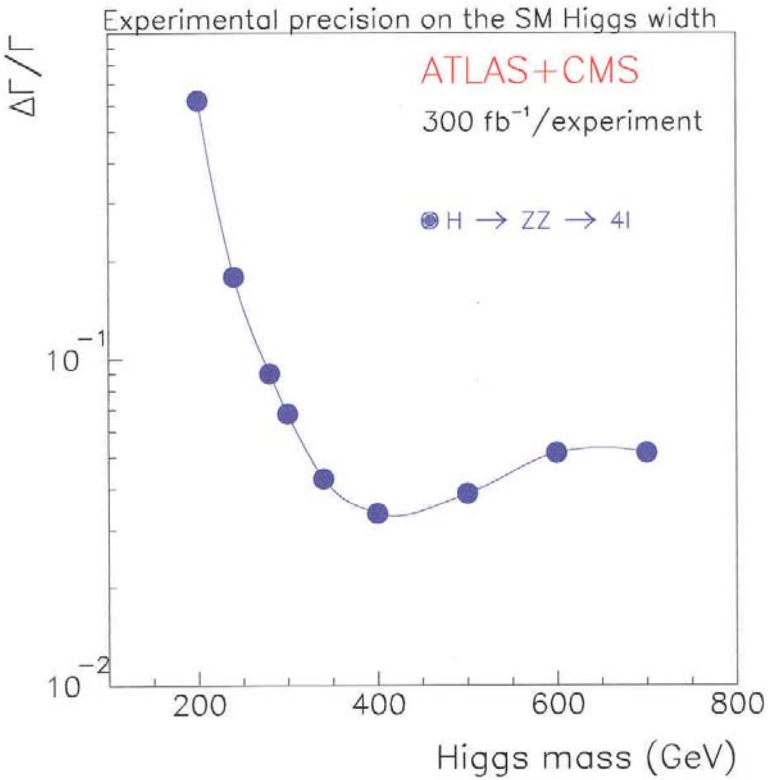


need 10 fb^{-1} for 5σ 115 GeV Higgs discovery (during 2007)

larger masses is much easier!

SM Higgs mass and width





Beyond the Standard Model

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

But, SM one loop corrections

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

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

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

If $\Lambda >> 1$ TeV, need "unnatural" tuning

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

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

Violation of naturalness = hierachy problem

Low-energy supersymmetry is a way out...

Supersymmetry

Maximal extension of the Poincaré group

3D rotations, pure boosts } Lorentz
Lorentz, 4D translations } Poincare′
Poincare′, SUSY translations } superPoincare′

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 $M_{SUSY} \approx$ 1 TeV

A natural way to break EW symmetry

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

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

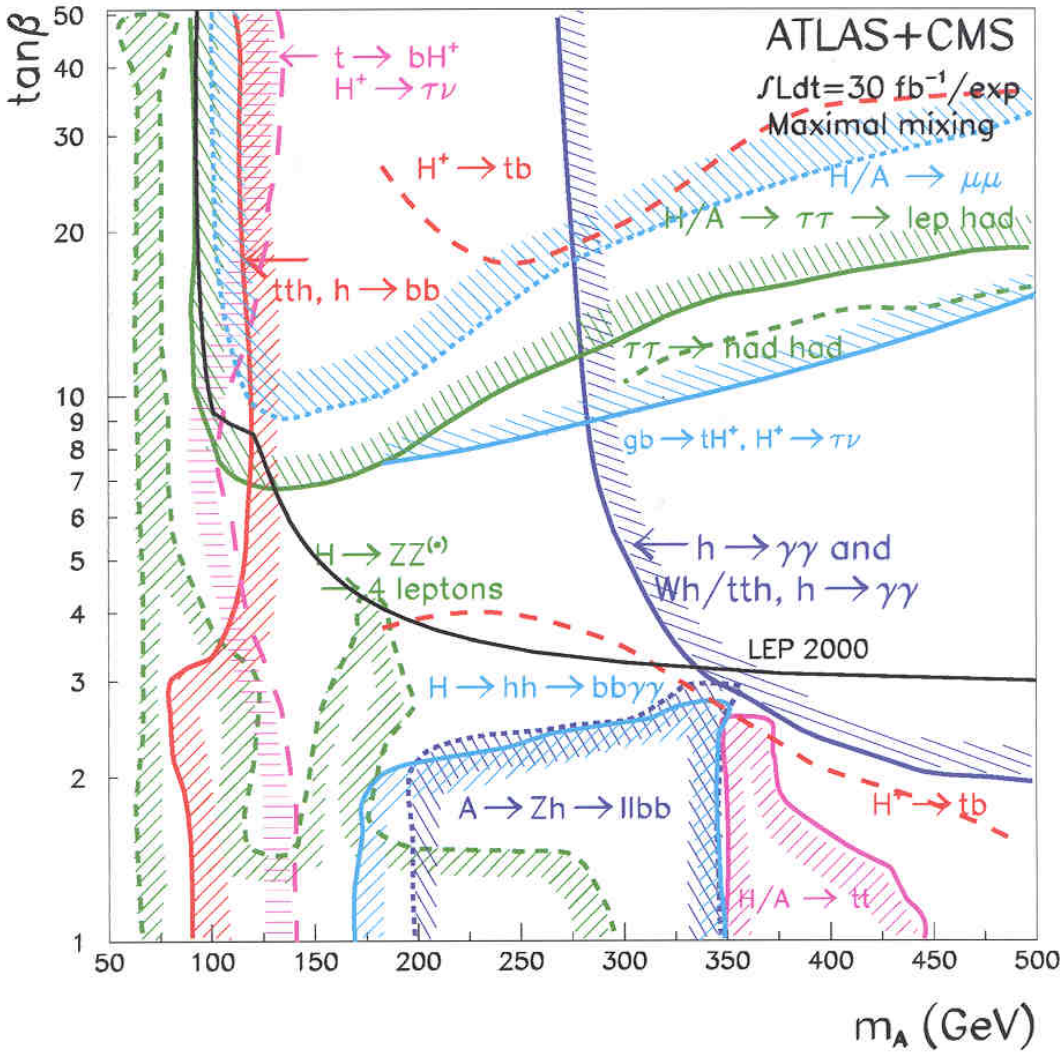
$$m_A \quad \text{and} \quad \tan\beta = \frac{\text{vev } H_u}{\text{vev } H_d}$$

Note that we also have the following mixings

$$B^0, W^0 \to \gamma, Z^0$$
$$\tilde{W}^\pm, \tilde{H}^\pm \to \chi_{1,2}^\pm$$
$$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \to \chi_{1,2,3,4}^0$$
$$\tilde{l}_L, \tilde{l}_R \to \tilde{l}_1, \tilde{l}_2$$
$$\tilde{q}_L, \tilde{q}_R \to \tilde{q}_1, \tilde{q}_2$$

with off-diagonal elements proportional to fermion masses

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

Conclusions

The SM Higgs sector still requires direct experimenta verification

Origin of electroweak symmetry breaking
Origin of mass

LEP results tantalizing

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