The Quest for the Origin of Mass

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The concept of Mass in Physics

- Classical: Newton, Einstein
- Quantum: matter waves, fields
- Standard Model: Higgs mechanism

Standard Model Higgs Searches

- LEP: status
- Tevatron: status and prospects
- LHC: prospects
  - ATLAS and Canada
- Beyond the SM: Supersymmetry

Conclusions

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The Quest for the Origin of Mass

Abstract

The concept of mass is at the very heart of physics. In Newtonian mechanics, mass appears as a primary characteristic of any physical object. But the concept of mass becomes more elusive, less fundamental, in modern formulations of the laws of nature. 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. A key ingredient, yet unverified, of the SM is the Higgs mechanism, responsible for the generation of the W and Z mass, themselves responsible for the apparent weakness of the weak force. 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 Higgs mechanism is the predicted existence of the Higgs particle. Its search 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, the SM and the Higgs mechanism, the status of searches for the SM Higgs particle (LEP and Tevatron) are briefly summarized, and prospects for future discoveries (Tevatron and LHC) are discussed. Canadian activities on the ATLAS detector at the LHC are also described.

Mass and Newton

The concept of mass lies at the heart of Newtonian physics

Sir Isaac Newton
1642-1727

$$F = ma = \frac{dp}{dt}$$ → **2nd Law**

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

Mass appears as a primary characteristic of any physical object

Lagrangian Formulation of Mechanics

Consider a (non relativistic) particle. All the information about its motion is given by its Lagrangian

$$L\left(x_i, \dot{x}_i, t\right) \qquad \text{Lagrangian} \qquad i = 1, 2, 3 \qquad \dot{x}_i = \mathrm{v}_i$$

$$S = \int dt \; L \qquad \text{action}$$

Hamilton's principle: $\delta S = 0 \quad \Rightarrow \quad \text{equations of motion}$

Euler-Lagrange equation: $\dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{x}_i} - \dfrac{\partial L}{\partial x_i} = 0$

For a free particle, experiment shows that $L = \frac{1}{2} m \mathrm{v}^2$

defines m!

symmetry of *L* $\Leftrightarrow$ conservation law

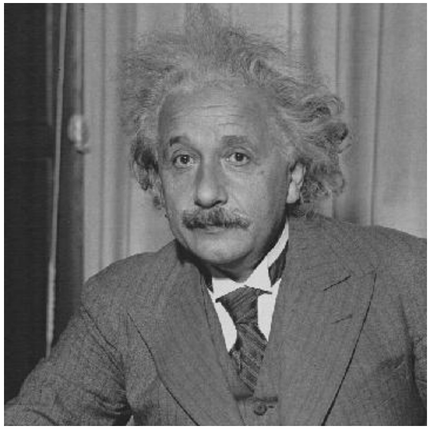
$$x_i \to x_i' = x_i + a_i \qquad \vec{p} = \text{constant}$$

$$t \to t' = t + t_\circ \qquad E = \text{constant}$$

$$x_i \to x_i' = \sum_j A_{ij} x_j \quad A^T A = I \qquad \vec{L} = \text{constant}$$

Mass and Einstein

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



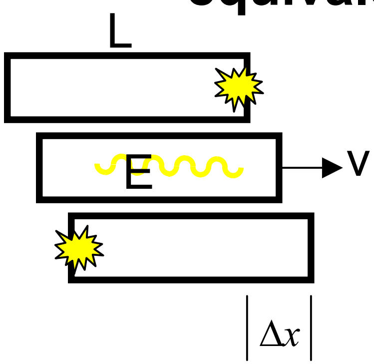
Albert Einstein
1879-1955

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

massless particles carry momentum!!

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

equivalence of mass and energy!!



momentum conservation $\quad M_{\mathrm{box}} \mathrm{v} = E/c$

Isolated system: CM fixed! $\quad M_{\mathrm{pulse}}(L - \Delta x) = M_{\mathrm{box}} \Delta x$

$$\Delta x = \mathrm{v} \Delta t = L \frac{\mathrm{v}}{\mathrm{v} + c} \quad \Longrightarrow \quad M_{\mathrm{pulse}} c^2 = E$$

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 $\Rightarrow$ $a = \dfrac{GM}{r^2}$ independent of *m*!

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

"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 ⟹ $E = h\nu = \hbar\omega \qquad p = \dfrac{h}{\lambda} = \hbar k$

The waves follow wave equations, e.g.

Schrödinger equation ⟹ non relativistic particle

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?

Wave Equation (non relativistic)

Free particle plane wave:

$$\psi \propto \exp\left[-i\left(\omega t - kx\right)\right] \qquad E = h\nu = \hbar\omega \qquad p = \frac{h}{\lambda} = \hbar k$$

Identify the following operators:

$$\hat{H}\psi = E\psi \quad \rightarrow \quad \hat{H} = i\hbar\frac{\partial}{\partial t}$$

$$\hat{p}\psi = p\psi \quad \rightarrow \quad \hat{p} = -i\hbar\frac{\partial}{\partial x}$$

Boldly go from particular to general:

Schrödinger equation

$$E = \tfrac{1}{2}m\mathrm{v}^2 + V = \frac{p^2}{2m} + V \quad \rightarrow \quad i\hbar\frac{\partial}{\partial t}\psi = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V\right]\psi$$

Wave Equation (relativistic)

Free particle plane wave: $\psi \propto \exp\left[-ik_\mu x^\mu\right] = \exp\left[-i\left(k^0 x^0 - \vec{k}\cdot\vec{x}\right)\right]$

$$p^\mu = \hbar k^\mu \qquad \hat{p}^\mu \psi = p^\mu \psi \quad \rightarrow \quad \hat{p}^\mu = i\hbar \frac{\partial}{\partial x_\mu} = i\hbar \partial^\mu$$

We use the relativistic energy-momentum relation $E^2 = \left(\vec{p}c\right)^2 + \left(mc^2\right)^2 \quad \rightarrow \quad p^\mu p_\mu = (mc)^2$

Klein-Gordon equation

$$p^\mu p_\mu - (mc)^2 = 0 \quad \rightarrow \quad \left[\hat{p}^\mu \hat{p}_\mu - (mc)^2\right]\varphi(x) = 0$$

$$\rightarrow \quad \left[\partial^\mu \partial_\mu + \left(m\tfrac{c}{\hbar}\right)^2\right]\varphi(x) = 0$$

$$\eta^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Dirac equation

$$p_\mu \gamma^\mu - mc = 0 \longrightarrow \left[\gamma^\mu, \gamma^\nu\right]_+ \equiv \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2\eta^{\mu\nu}$$

$$p^\mu p_\mu - (mc)^2 = 0 \qquad \left[i\hbar\gamma^\mu \partial_\mu - mc\right]\psi(x) = 0$$

From now on we use the "natural units" $\hbar = c = 1$

Wave Equation (relativistic)

$$A^\mu(x) \equiv \left(\phi, \vec{A}\right)$$

$$F^{\mu\nu}(x) = \begin{array}{c} \nu \rightarrow \begin{array}{cccc} 0 & 1 & 2 & 3 \end{array} \\ \begin{pmatrix} 0 & -E_1 & -E_2 & -E_3 \\ E_1 & 0 & -B_3 & B_2 \\ E_2 & B_3 & 0 & -B_1 \\ E_3 & -B_2 & B_1 & 0 \end{pmatrix} \end{array}$$

Maxwell equation

$$\partial_\mu F^{\mu\nu} = 0 \qquad F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$$

$$\text{or} \quad \partial_\mu \partial^\mu A^\nu - \partial^\nu\left(\partial_\mu A^\mu\right) = 0$$

Maxwell equation is invariant under the gauge (local) transformation

$$A^\mu \rightarrow A'^\mu = A^\mu + \partial^\mu f \qquad \forall f(x)$$

Lorentz gauge: $\partial_\mu A^\mu = 0 \Longrightarrow \partial_\mu \partial^\mu A^\nu = 0 \leftarrow p^\mu p_\mu = 0$

Each component of the free field *A* follows a massless Klein-Gordon equation!

Proca equation

$$\partial_\mu G^{\mu\nu} + m^2 Z^\mu = 0 \qquad \mathrm{G}^{\mu\nu} \equiv \partial^\mu Z^\nu - \partial^\nu Z^\mu$$

$$\text{or} \quad \left(\partial_\mu \partial^\mu + m^2\right) Z^\nu = 0$$

$\partial_\mu Z^\mu = 0$ always. No gauge invariance

Each component of the free field *Z* follows a Klein-Gordon equation!

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?

Lagrangian Formulation

We now consider the Lagrangian density of a field

$$\mathscr{L}\left(\psi, \partial^{\mu}\psi, x^{\mu}\right) \qquad \text{Lagrangian density} \qquad \mu = 0, 1, 2, 3$$

$$S = \int d^4x \; \mathscr{L} \qquad \text{action}$$

Hamilton's principle: $\delta S = 0 \quad \Rightarrow \quad$ equations of motion

Euler-Lagrange equation: $\partial_{\mu}\left(\dfrac{\partial \mathscr{L}}{\partial\left(\partial_{\mu}\psi\right)}\right) - \dfrac{\partial \mathscr{L}}{\partial \psi} = 0$

Free Klein-Gordon: $\mathscr{L}_{KG} = \left(\partial_{\mu}\varphi\right)^{*}\left(\partial^{\mu}\varphi\right) - m^2\varphi^{*}\varphi$ spin 0

global symmetry of $\mathscr{L}$ $\Leftrightarrow$ conservation law

$$\left.\begin{array}{lll} x^{\mu} \to x'^{\mu} = x^{\mu} + a^{\mu} & & p^{\mu} = \text{constant} \\ x^{\mu} \to x'^{\mu} = \Lambda^{\mu\nu}x_{\nu} & \Lambda^{T}\eta\Lambda = \eta & M^{\mu\nu} = \text{constant} \;\to\; \text{spin } 0 \\ \varphi \to \varphi' = \varphi e^{-i\varepsilon} & & Q = \text{constant} \end{array}\right\} \text{of the field!!}$$

… the number of particles is not constant!

Lagrangian Formulation

Free Dirac: $\mathscr{L}_D = \bar{\psi}\left[i\gamma^\mu \partial_\mu - m\right]\psi \qquad \bar{\psi} \equiv \psi^\dagger \gamma^0$ spin 1/2

global symmetry of $\mathscr{L}$ $\Leftrightarrow$ conservation law

$\psi \to \psi' = \psi e^{-i\varepsilon}$ $\qquad Q = \text{constant}$

Free Maxwell: $\mathscr{L}_M = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$ spin 1

gauge (local) symmetry of $\mathscr{L}$

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

Free Proca: $\mathscr{L}_P = -\frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \frac{1}{2} m^2 Z^\mu Z_\mu$ spin 1

no local symmetry of $\mathscr{L}$: *the mass term violates gauge invariance!*

Gauge Invariance and the EM Interaction

Consider the interaction between the Dirac field and Maxwell field

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

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

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

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

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

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

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

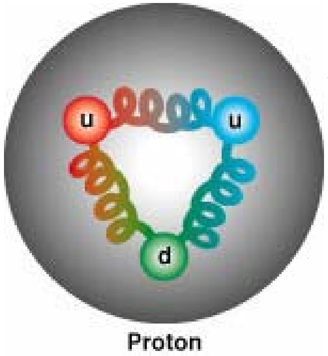
and prescribes the form of the interaction!! $\Longrightarrow$ QED

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%!

$m = E$ again! → energy of gluons and quarks in baryons

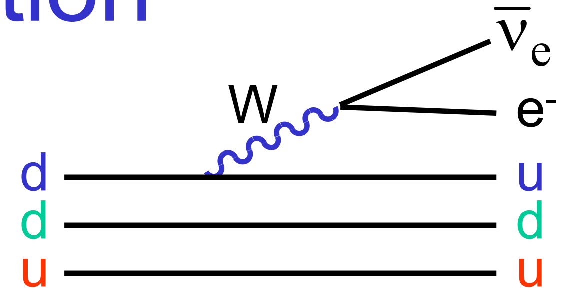
Protons and neutrons make up over 99% of the mass of ordinary matter...

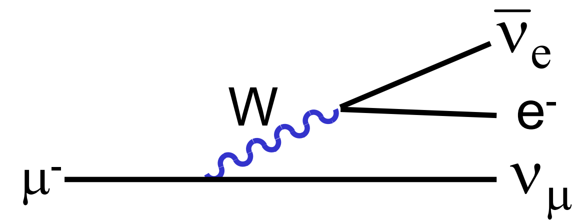
We are getting closer to "mass without mass"!

Weak Interaction

We want to obtain the weak interaction from a gauge principle

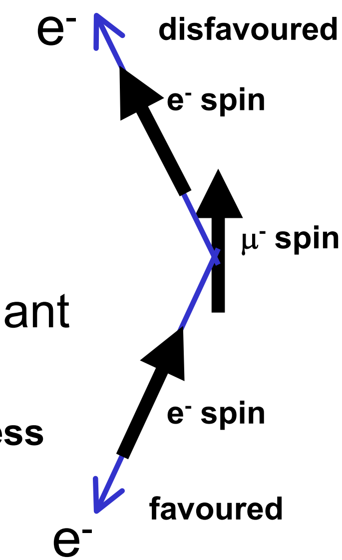
But the weak interaction is mediated by massive particles, and boson mass terms violate gauge invariance...





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 $\neq$ helicity spin flip!

handedness

mass term mixes chirality $\bar{\psi}\psi = \bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L$

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

$\Longrightarrow$ 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 $\varphi(x) \neq 0$

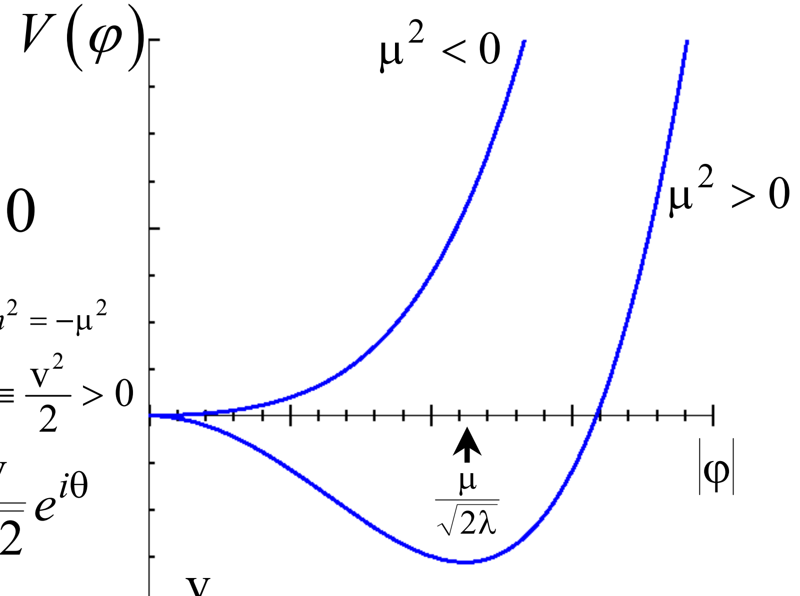
Lorentz invariance $\Longrightarrow$ $\varphi(x)$ is a scalar

$\varphi(x)$ is a complex scalar

Goldstone model: consider

$$\mathscr{L} = \left(\partial_\mu \varphi\right)^* \left(\partial^\mu \varphi\right) - V(\varphi)$$

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



$\mu^2 < 0 \Longrightarrow$ **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 φ(*x*) from equilibrium. We get

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

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

We can interpret: $\sigma \to$ 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...

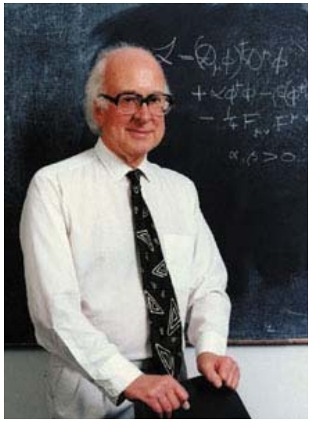
We need a hidden symmetry mechanism that does not generate physical massless Goldstone bosons

Higgs Model

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

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

Invariant under
$$\varphi \xrightarrow{\varepsilon(x)} \varphi' = e^{-i\varepsilon(x)} \varphi$$
$$A^\mu \xrightarrow{\varepsilon(x)} A'^\mu = A^\mu + \tfrac{1}{q} \partial^\mu \varepsilon$$



Higgs
1929-

$\mu^2 < 0 \Longrightarrow$ **Scalar electrodynamics with 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, $\theta = 0 \to \varphi_0 = \frac{v}{\sqrt{2}} > 0$
always possible because of global U(1) phase invariance

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

Higgs Model (continued)

Obtain

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

Aaarg!

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

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

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

and n.d.f would NOT add up ⟶

$$\begin{array}{lll} & & \text{n.d.f} \\ \text{Initially:} & \left\{\begin{array}{l}\text{complex } \varphi \\ \text{real massless } A^\mu\end{array}\right. & \begin{array}{l}\to 2 \\ \to 2\end{array} \Big\} \to 4 \\ \text{After :} & \left\{\begin{array}{l}\text{real massive } \sigma \\ \text{real massless } \eta \\ \text{real massive } A^\mu\end{array}\right. & \begin{array}{l}\to 1 \\ \to 1 \\ \to 3\end{array} \Big\} \to 5 \end{array}$$

!

$\mathscr{L}$ contains an unphysical field which can be eliminated through a gauge transformation yielding the form

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

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

Higgs Model (end)

In this gauge, we obtain

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

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

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

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

and n.d.f do add up $\Longrightarrow$

		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!! $\Longrightarrow$ **$\sigma(x)$ is a Higgs boson field**

vector boson acquires mass without spoiling gauge invariance
$\Longrightarrow$ **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...

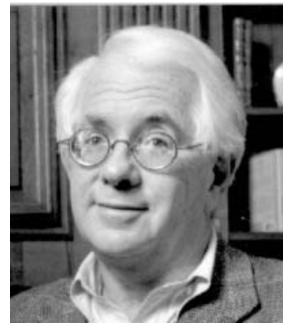
…if a rumor crosses the room...

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

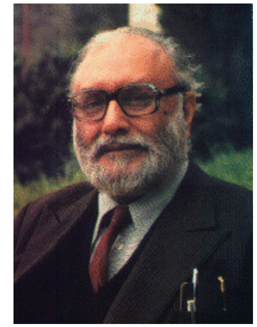
ATLAS educational web page, adapted from an idea from Dr D. J. Miller

The Standard Model
of Electroweak and Strong Interactions

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



Glashow
1932-



Salam
1926-1996

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

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

bosons — **radiation**

$U(1)_Y$	B	$\xrightarrow{\cancel{EW}}$	γ	electro-weak
$SU(2)_L$	W_1, W_2, W_3		W^+, W^-, Z^0	
$SU(3)_C$	$g_{1\text{-}8}$		$g_{1\text{-}8}$	strong
Higgs doublet	$\varphi_1+i\varphi_2$, $\varphi_3+i\varphi_4$		H^0	

SM Higgs Interactions

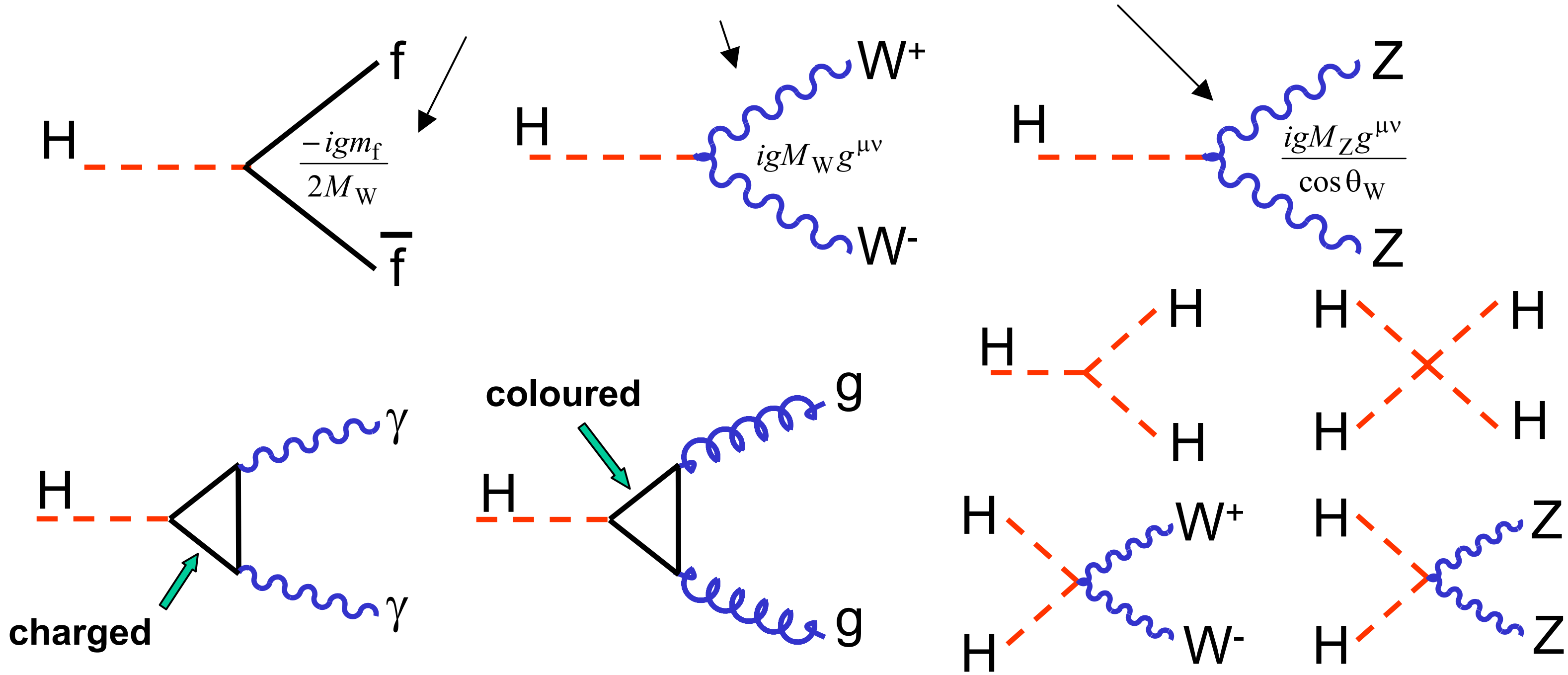
SM ⟶ Higgs mechanism with $U(1)_Y \times SU(2)_L$ gauge

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

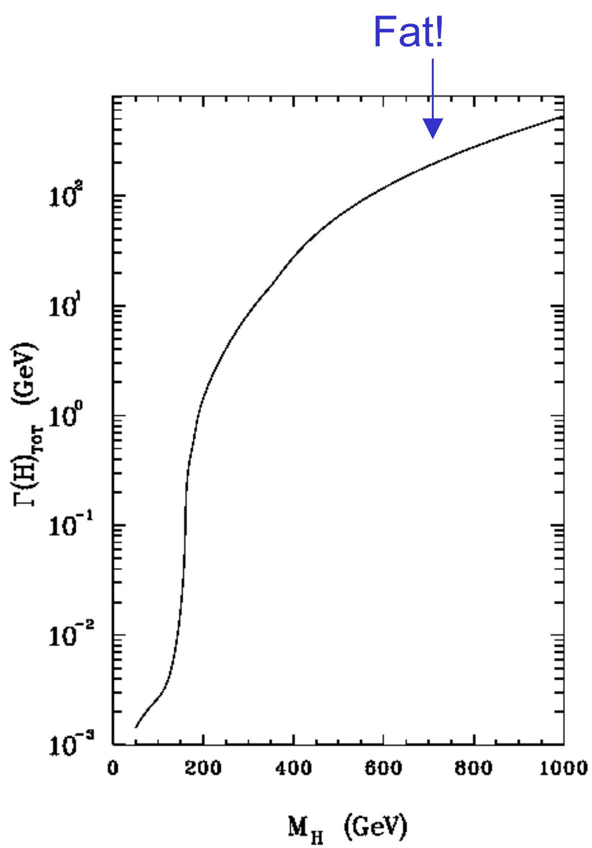
$$v = \left(\sqrt{2}G_F\right)^{-1/2} = 246\ \mathrm{GeV}$$

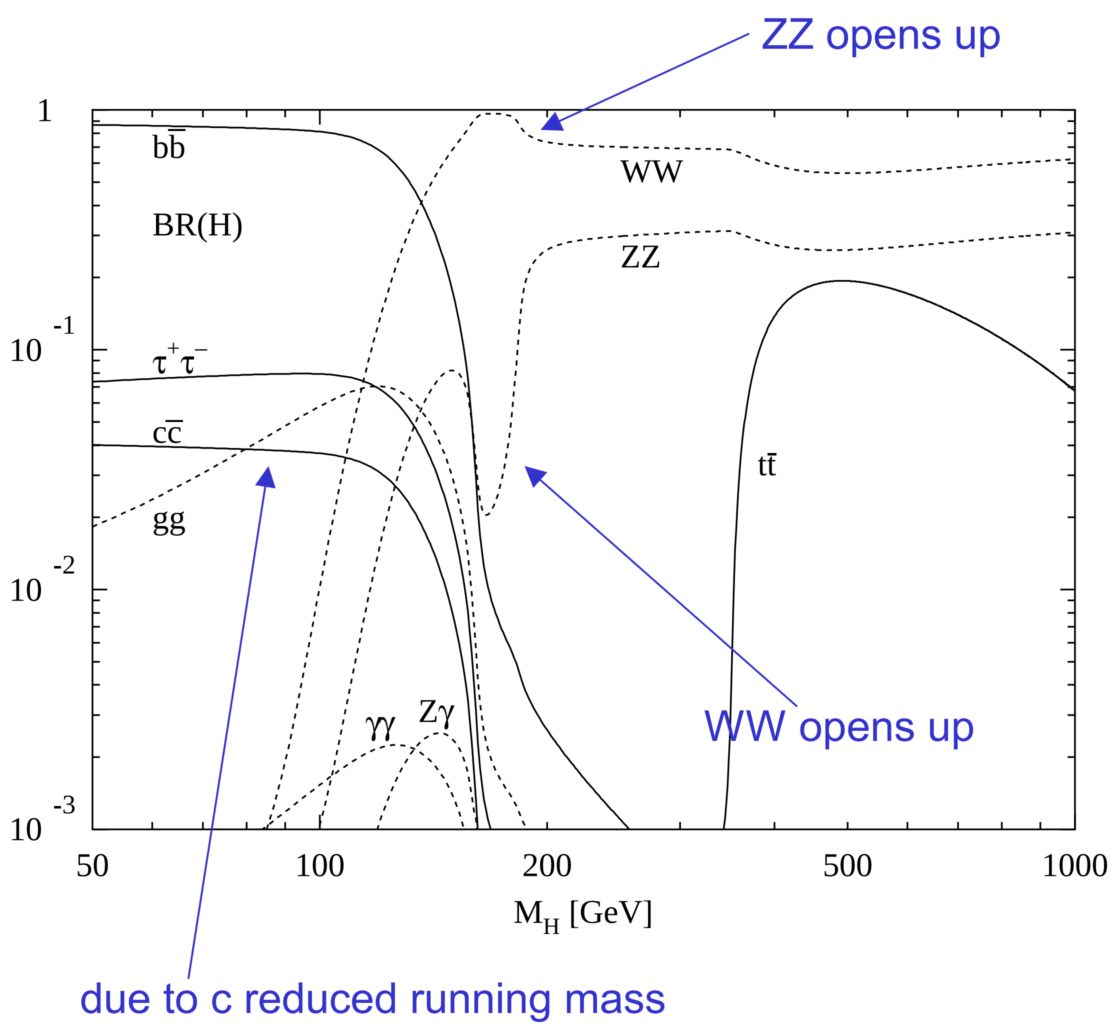
$\varphi(x)$ coupling with massless fermion fields ⟶ fermion masses

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



SM Higgs Decays

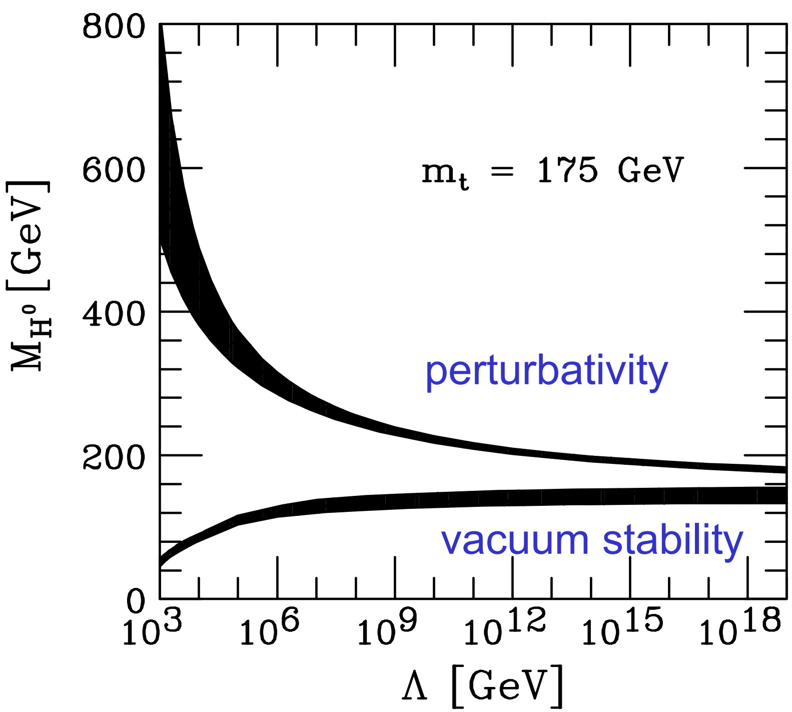




Theoretical Constraints on M_H

M_H is a free parameter of SM

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

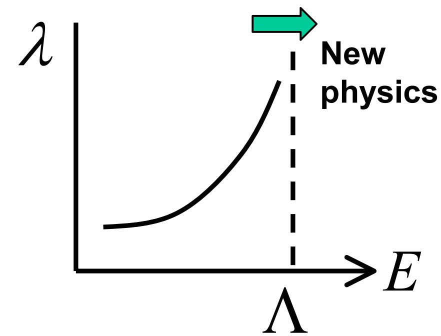


$$130\,\mathrm{GeV} \approx< M_H \approx< 180\,\mathrm{GeV}$$

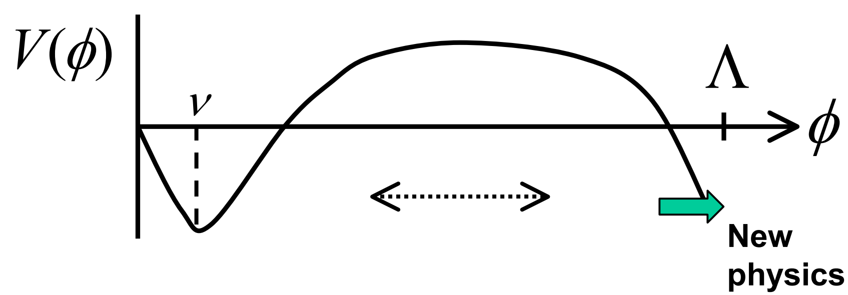
then, in principle consistent with $\Lambda = M_{PL}$

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

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

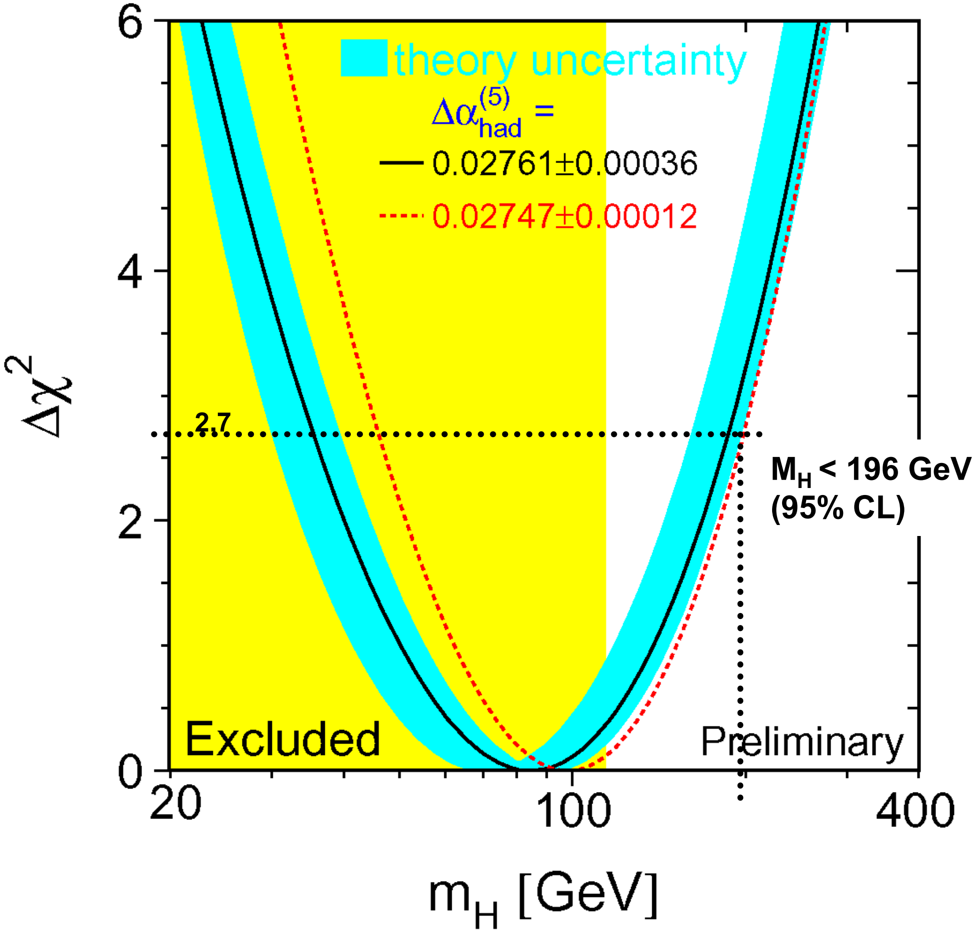


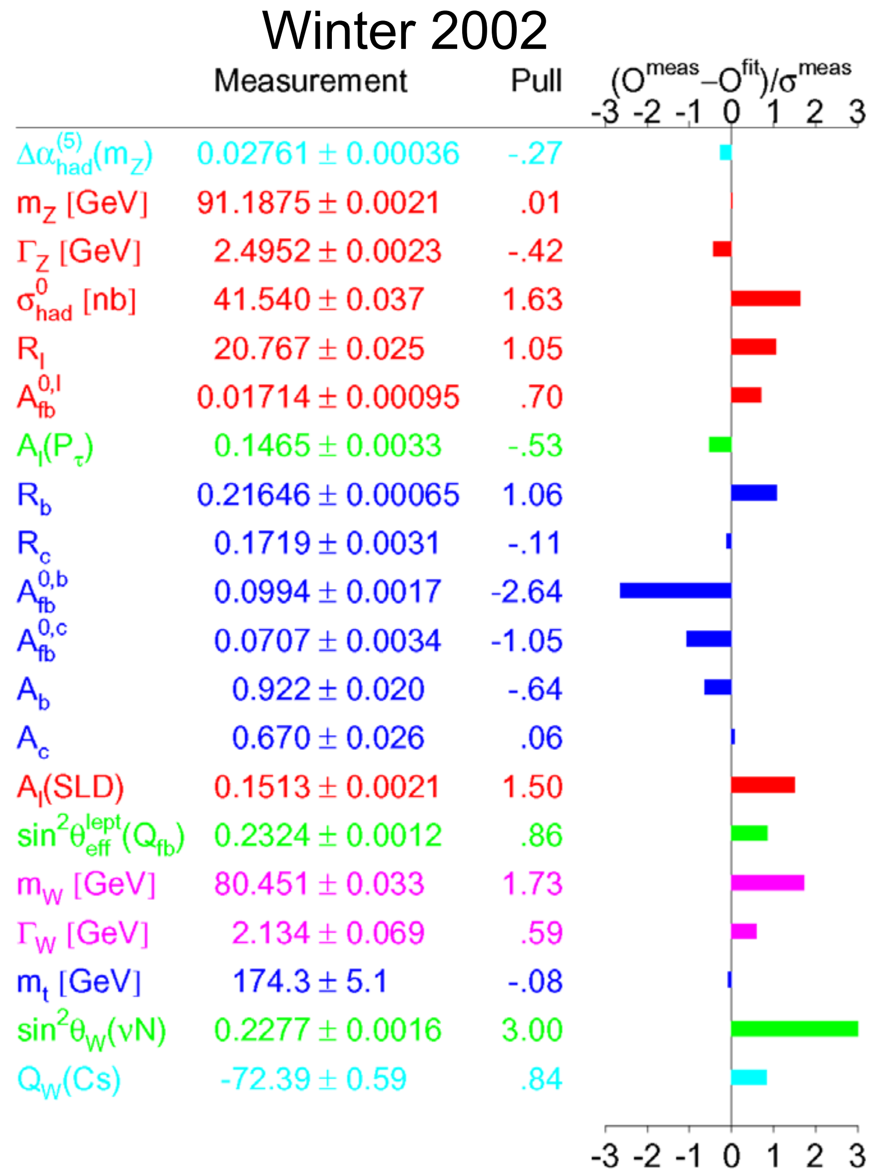
M_H is too small: the higgs potential develops a second (global!) minimum values of the scalar field of the order of Λ



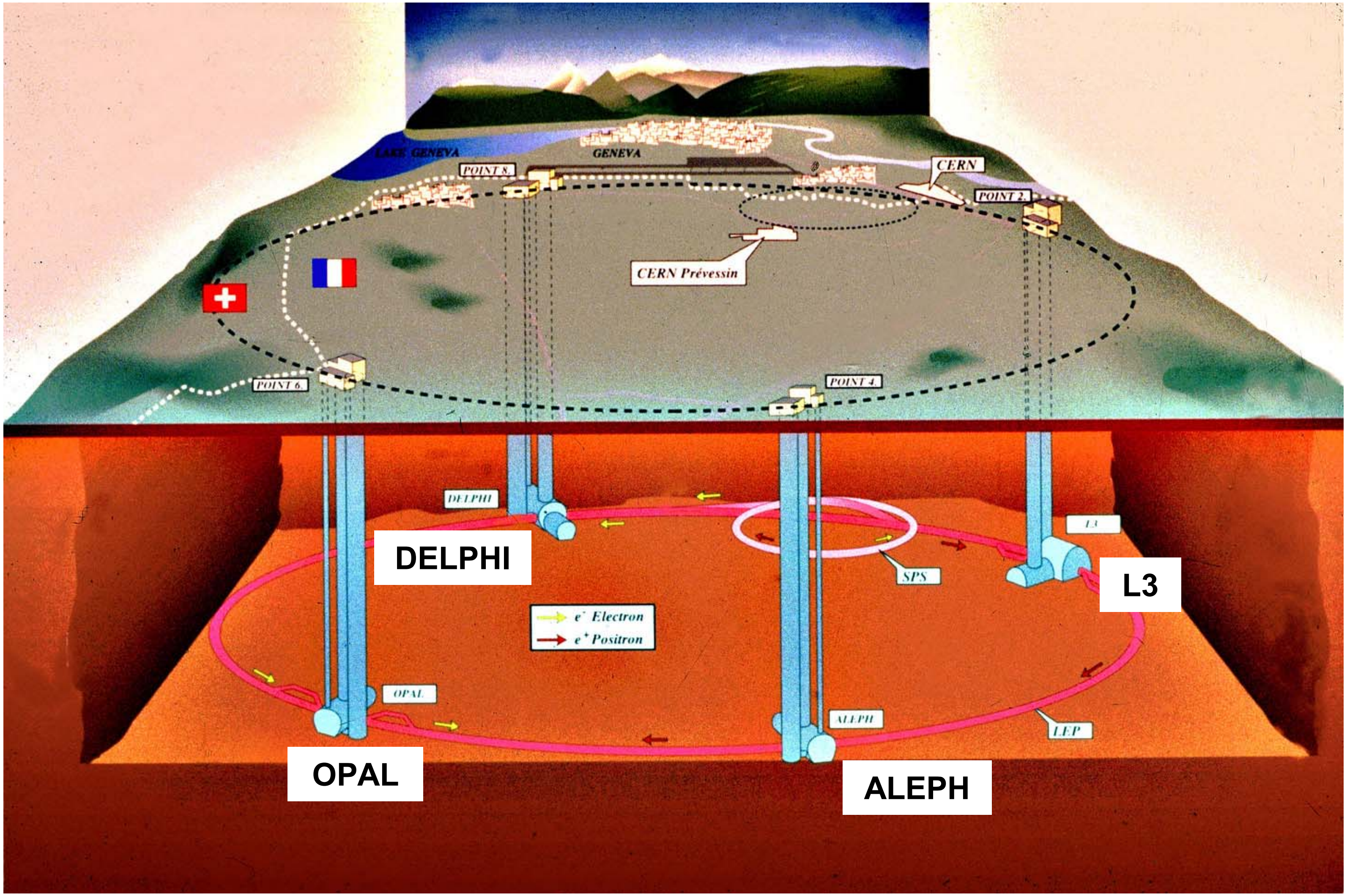
Experimental Constraints on M_H

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





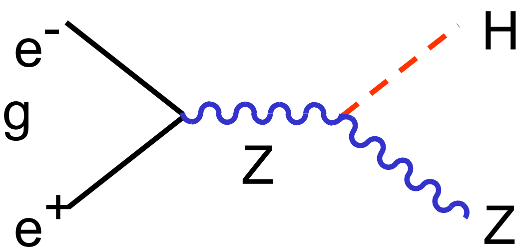
Large Electron Positron Collider



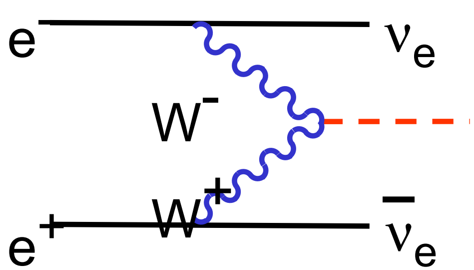
LEP Data Sets and SM Higgs Production

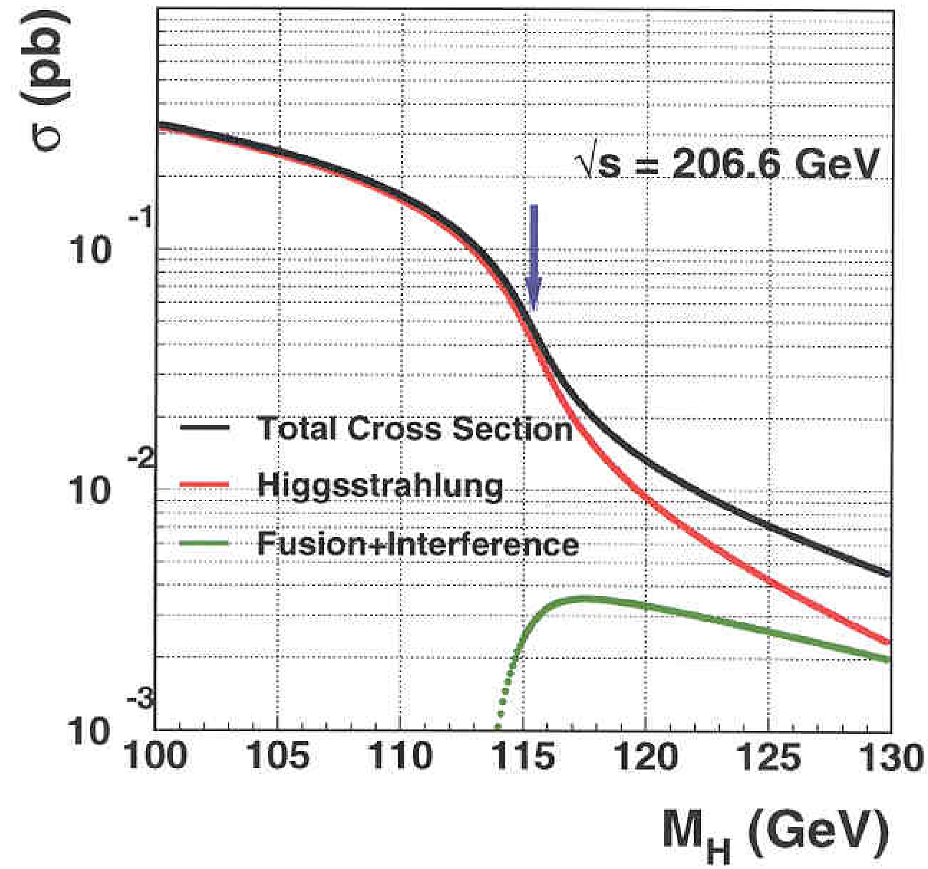
Stage	$\sqrt{s}$	Year	Luminosity
LEP 1	$\approx M_{Z^0}$	1989-1995	175 pb^{-1}
LEP 1.5	130-140 GeV	1995	5 pb^{-1}
LEP 2	161 GeV	1996	10 pb^{-1}
	172 GeV	1996	10 pb^{-1}
	183 GeV	1997	55 pb^{-1}
	189 GeV	1998	180 pb^{-1}
	192–202 GeV	1999	230 pb^{-1}
	200–209! GeV	2000	220 pb^{-1}

Higgsstrahlung



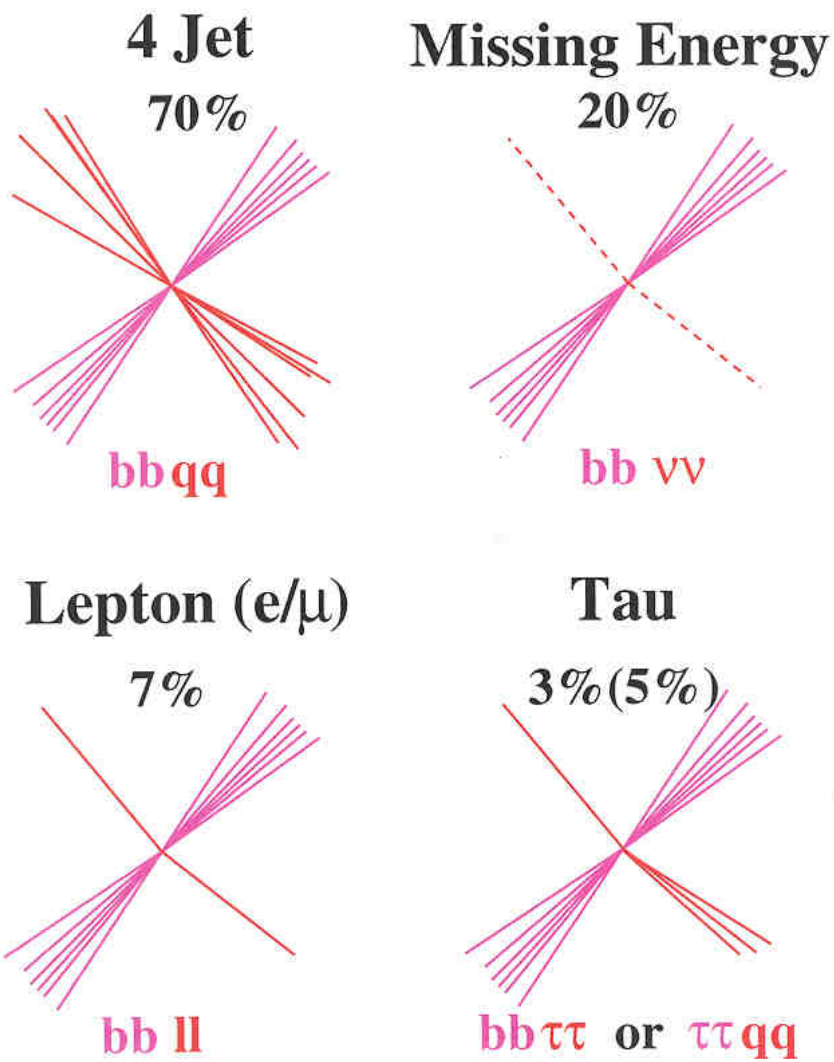
Fusion

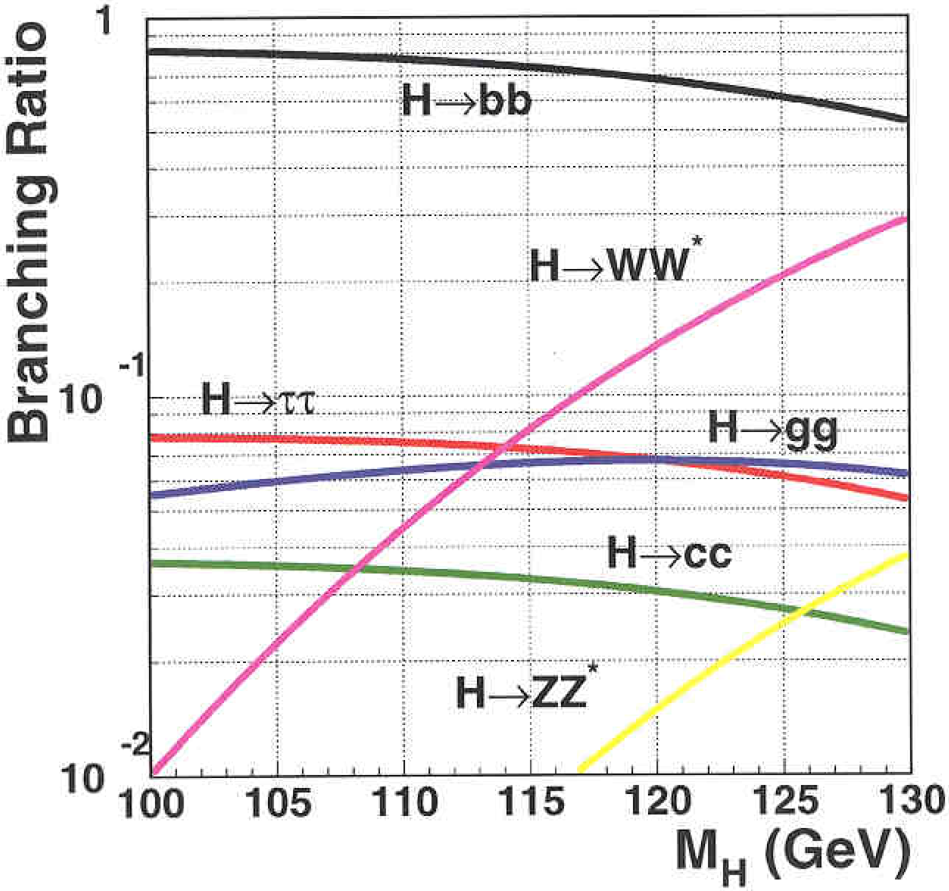




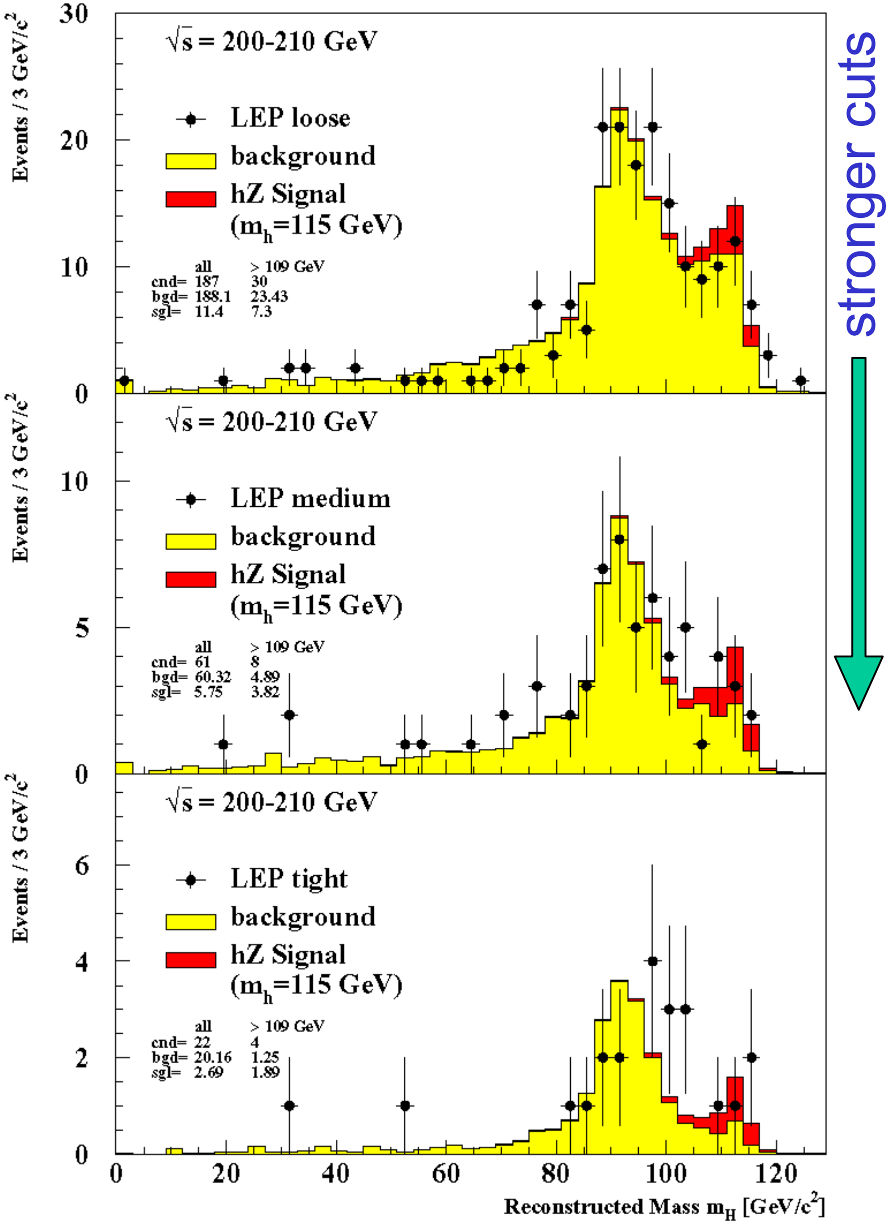
for example at 200-209 GeV we get, for a 115 GeV mass Higgs,
$0.05\ \text{pb} \times 220\ \text{pb}^{-1} = 11$ events produced!

SM Higgs Topologies





Higgs Reconstructed Mass Distribution



LEP Higgs Working Group

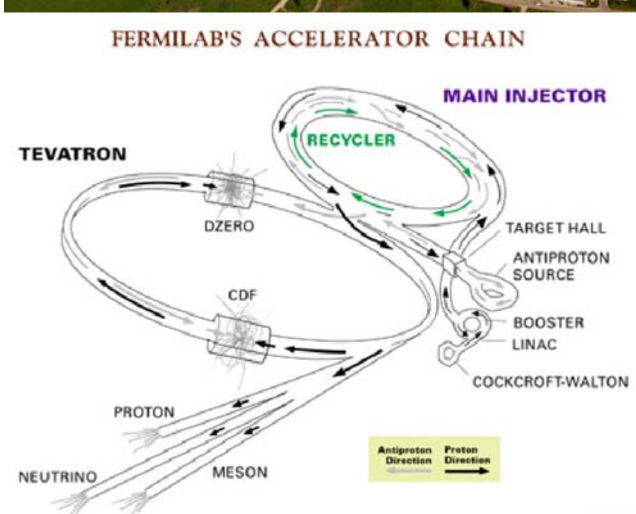
$$M_H > 114\ \text{GeV}\ @95\%\ \text{CL}$$

Signal hypothesis yields a mass of 116 GeV, but only about 2σ above background

LEP is now 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

$\approx 1.6\times10^{31}$ 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

$\approx 2\times10^{32}$ cm^{-2}s^{-1}

>2 fb^{-1}per exp.

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

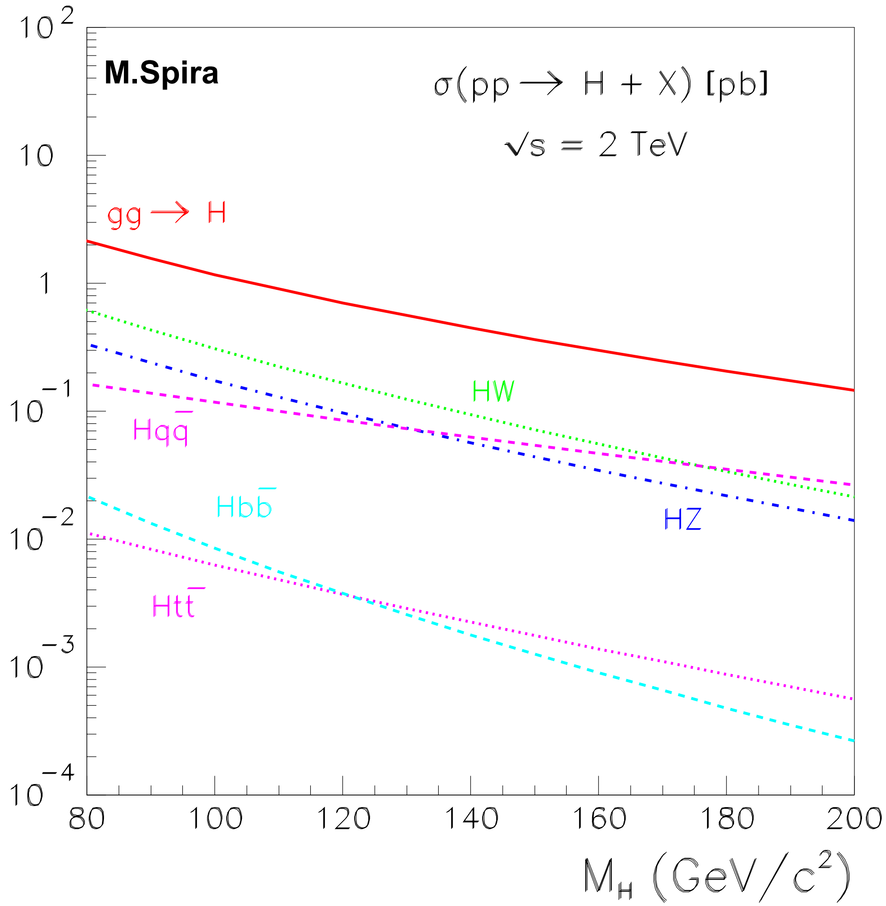
more bunches, 132 ns

goal, by end 2007

$\approx 5\times10^{32}$ cm^{-2}s^{-1}

>15 fb^{-1}per exp.

SM Higgs Production at the Tevatron



E. Barberis

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

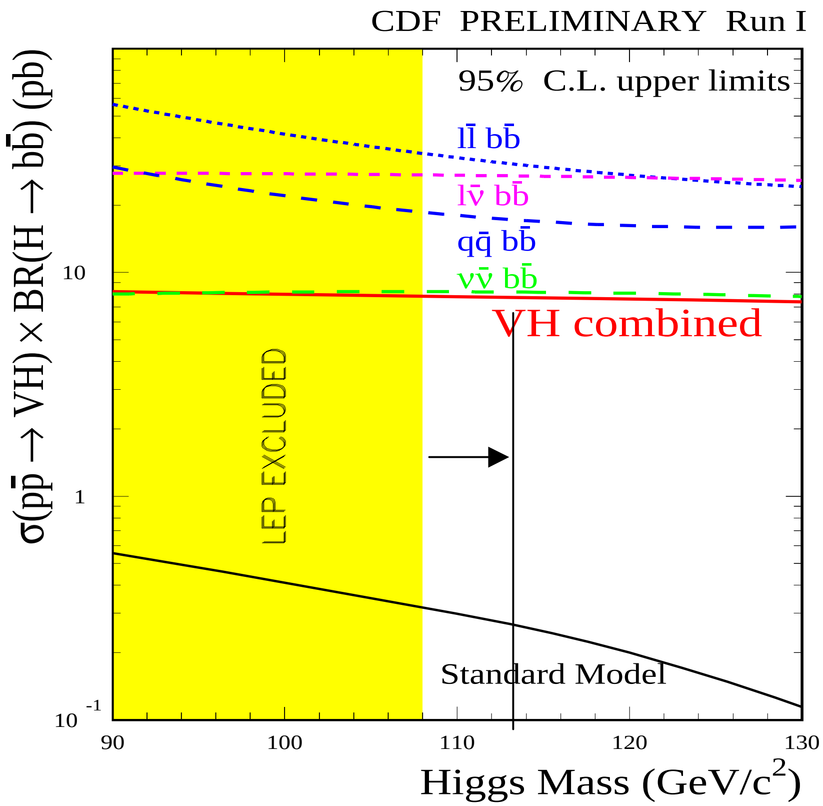
	σ[pb] (m_H=100 GeV)
$gg \to H$	1.0
WH	0.3
ZH	0.18
WZ	3.2
Wbb	11
tt	7.5
tb+tq+tbq	3.4
QCD	$O(10^6)$

WH/ZH production are preferred

SM Higgs Searches at the Tevatron

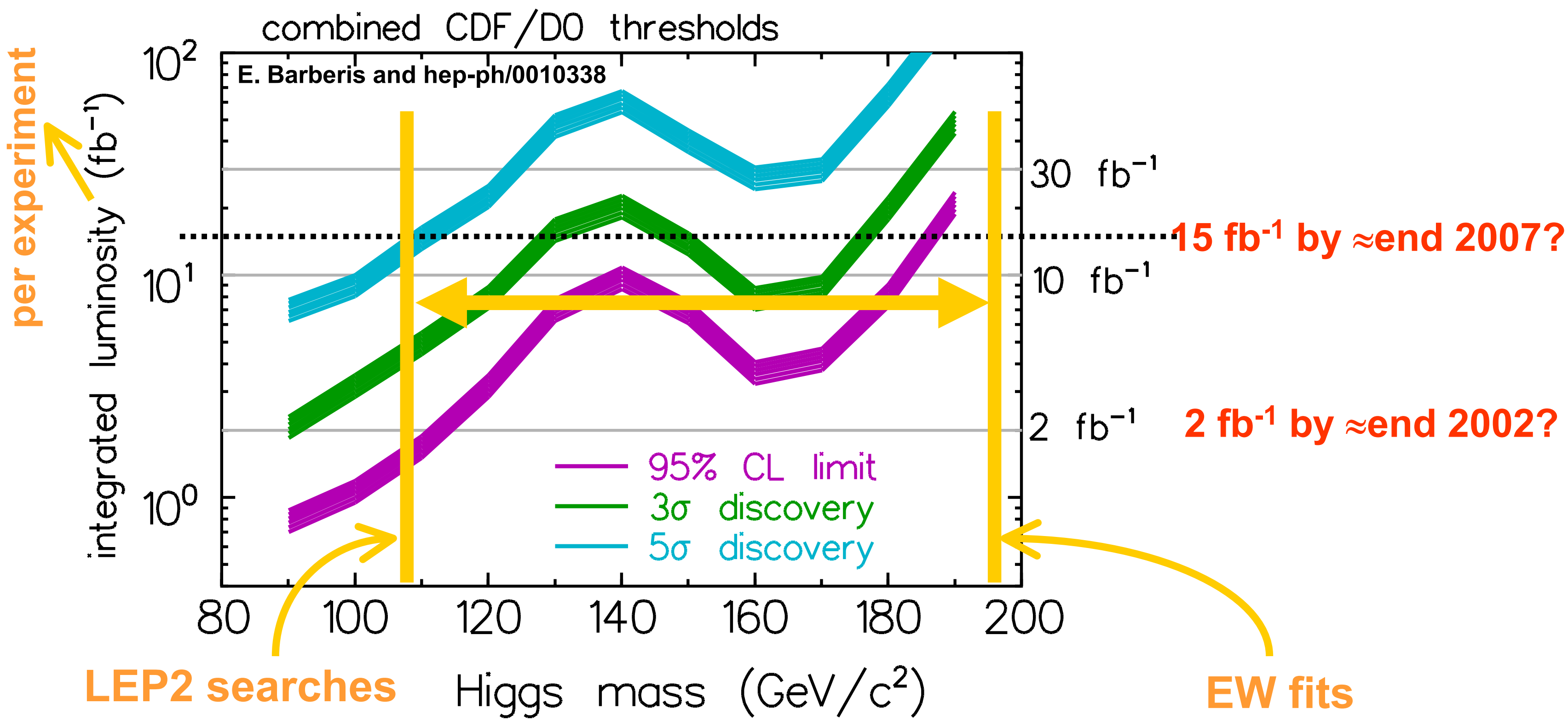
CDF: SVX b-tagging

WH → ννbb	1 and 2 b-tag
WH → *l*νbb	1 and 2 b-tag
ZH → ννbb	1 and 2 b-tag
ZH → *ll*bb	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

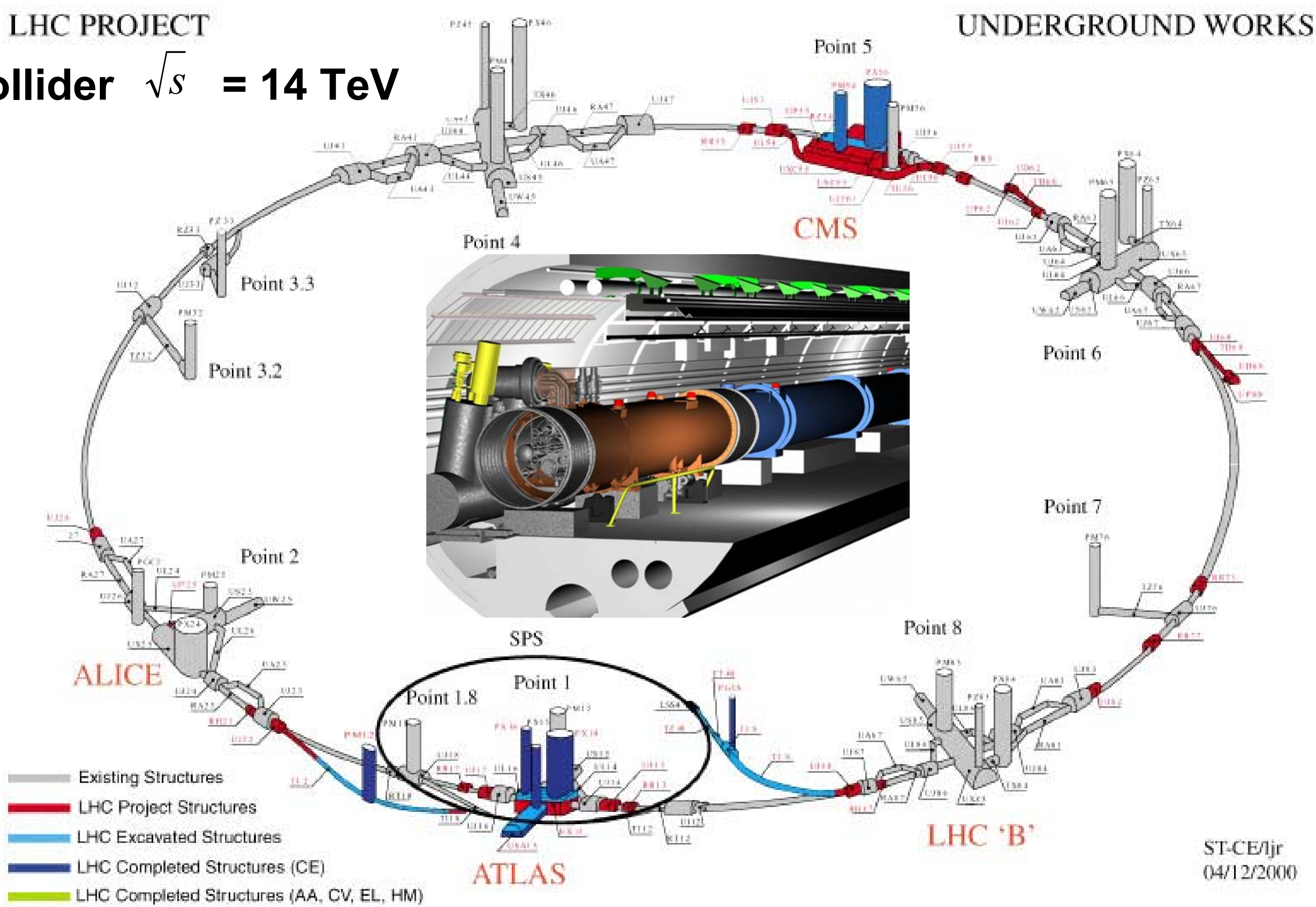
10 fb^{-1} 95% CL exclusion to M_H≈180 GeV in the absence of signal

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

Aerial View of CERN

Large Hadron Collider at CERN

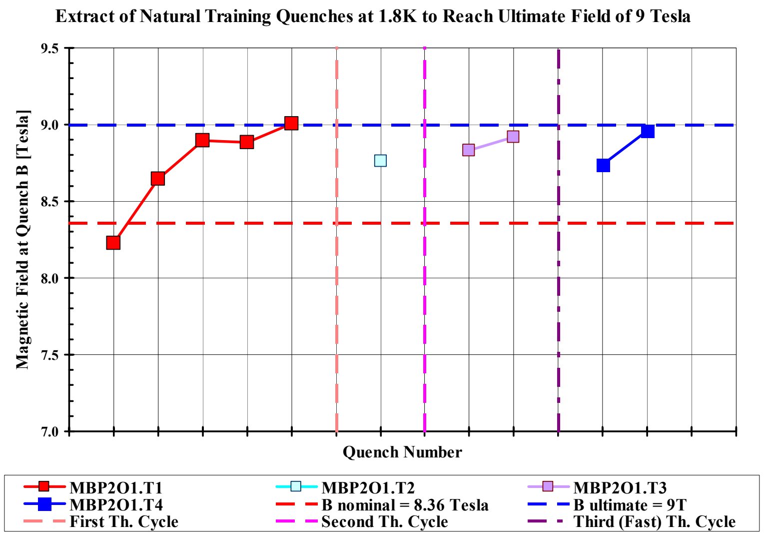
pp collider $\sqrt{s}$ = 14 TeV

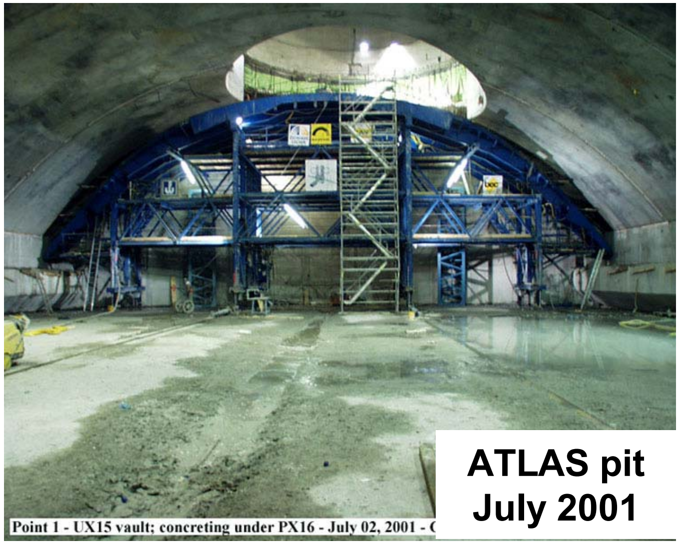


Large Hadron Collider at CERN

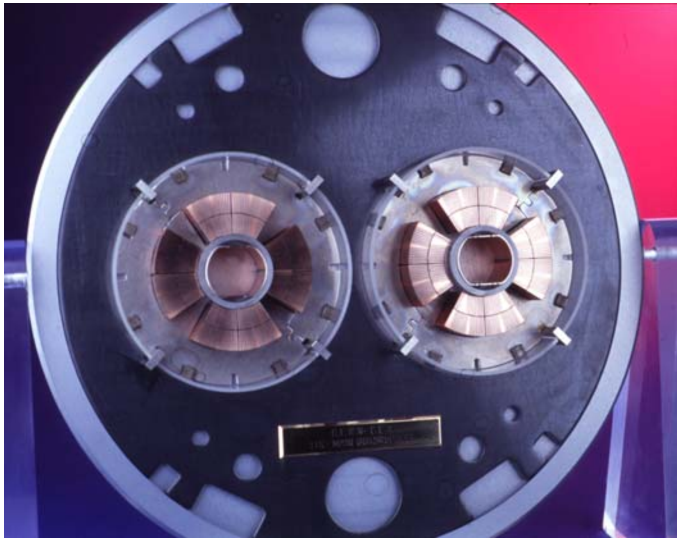
pp collider $\sqrt{s}$ = 14 TeV

2835+2835 bunches, 25 ns
octan test in 2004
ring cooled by end 2005
beam for physics 2006
$\approx 2\times10^{33}$ 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 July 2001



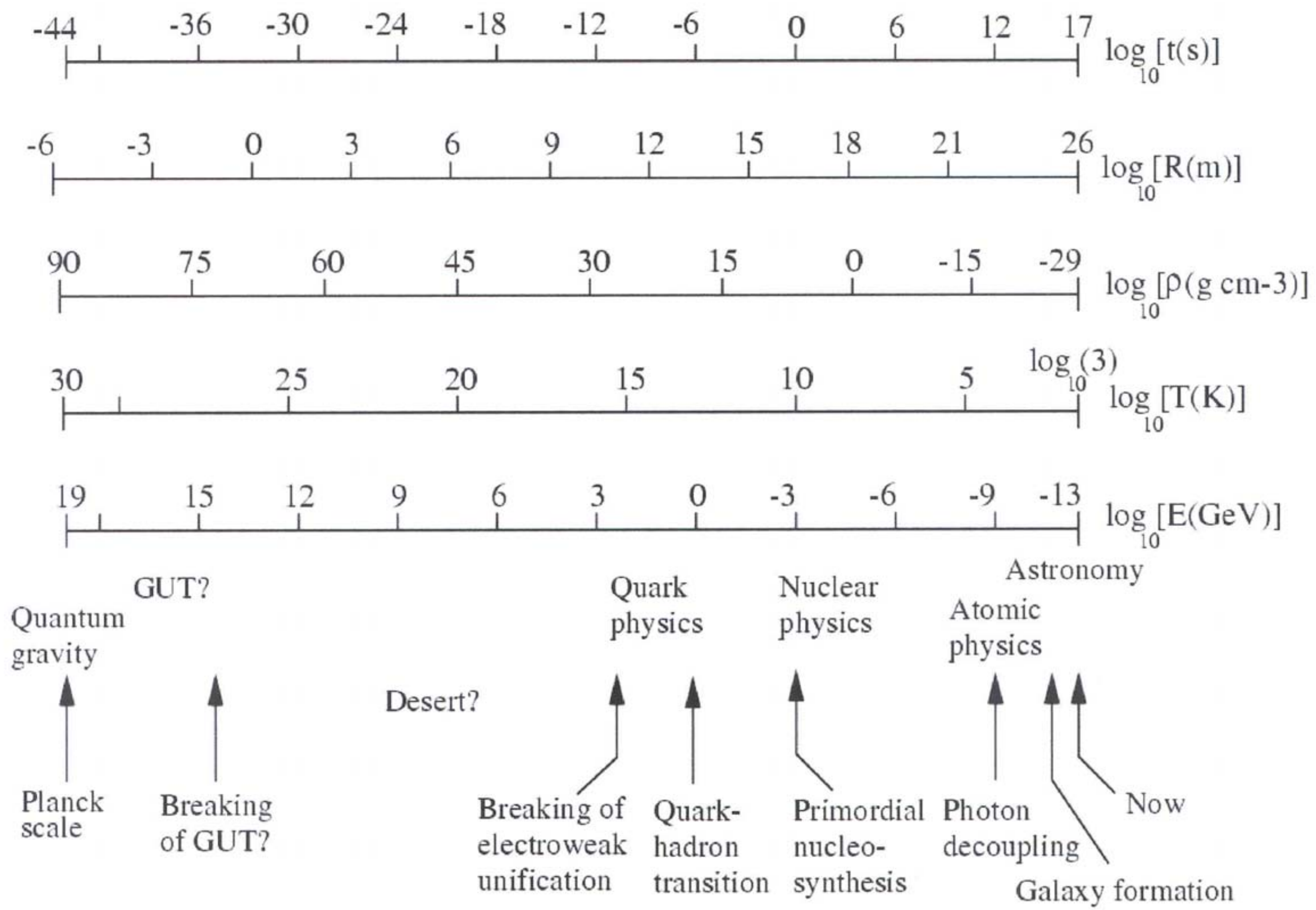
5000 superconducting magnets (1296 dipoles) Cu-clad Nb-Ti cables to operate at 1.9K with up to 15kA

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

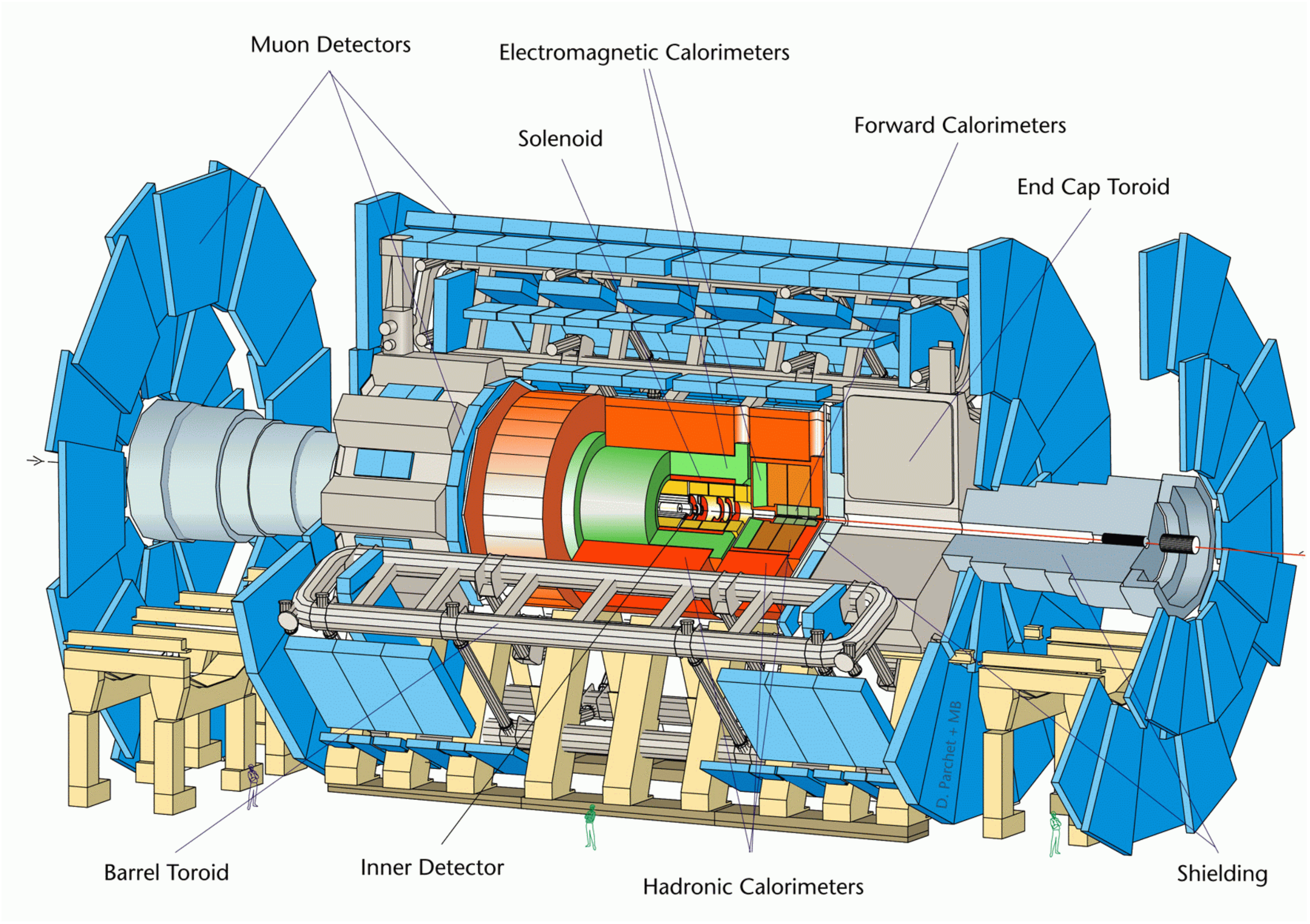
LHC: 25×E and 10k×L of SPS for same power

Space, Time and the Energy Frontier

The "History" of the Universe from the Planck time to the present, showing how the size of the presently observable universe R, the average density ρ, the temperature T, and the energy per particle kT, have varied with time t according to the hot big bang model.



The ATLAS Detector



Alberta
Carleton
CRPP
Montréal
SFU
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.)
T. Ince (M.Sc.)
V. Singh (M.Sc.)

Canada and ATLAS

Activities focused on Liquid Argon Calorimetry

4 Major Projects Funded by Major Installation Grants

Endcap Hadronic Calorimeter

Forward Hadronic Calorimeter

Frontend-Board Electronics

Endcap Signal Cryogenics Feedthroughs

New Initiatives

ATLAS Computing

ATLAS OO Software

Other Activities

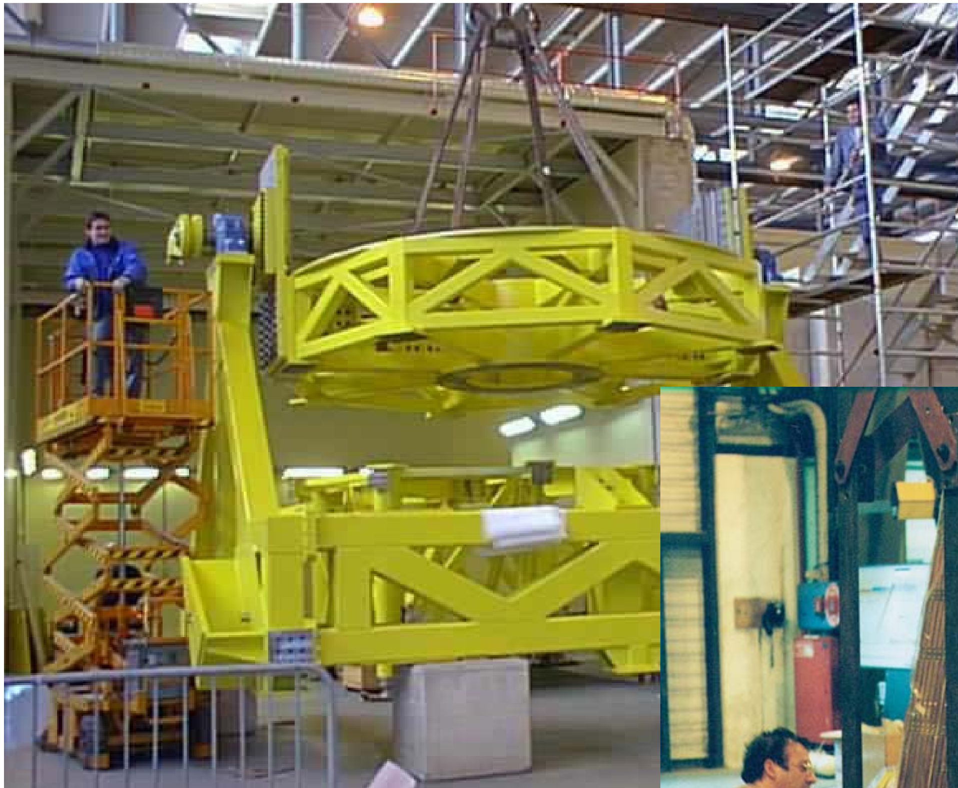
Radiation Hardness Studies

Pixel Detector Contribution

Physics Studies

Alberta
Carleton
CRPP
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

Canada and ATLAS in pictures



Endcap calorimeter rotator at CERN

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CRPP
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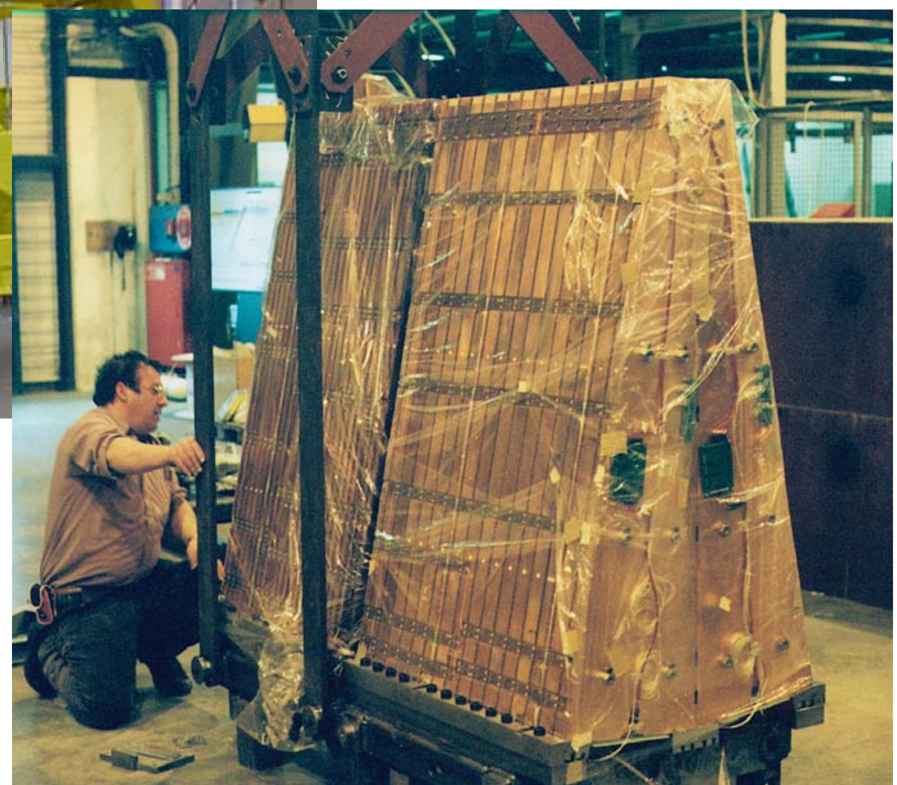
SFU
Toronto
TRIUMF
UBC
Victoria
York



One of many endcap calorimeter modules

Canada and ATLAS in pictures

Forward calorimeter module 1 under construction

Alberta
Carleton
CRPP
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

Forward calorimeter module 2 under construction

Canada and ATLAS in pictures

High density endcap signal feedthroughs

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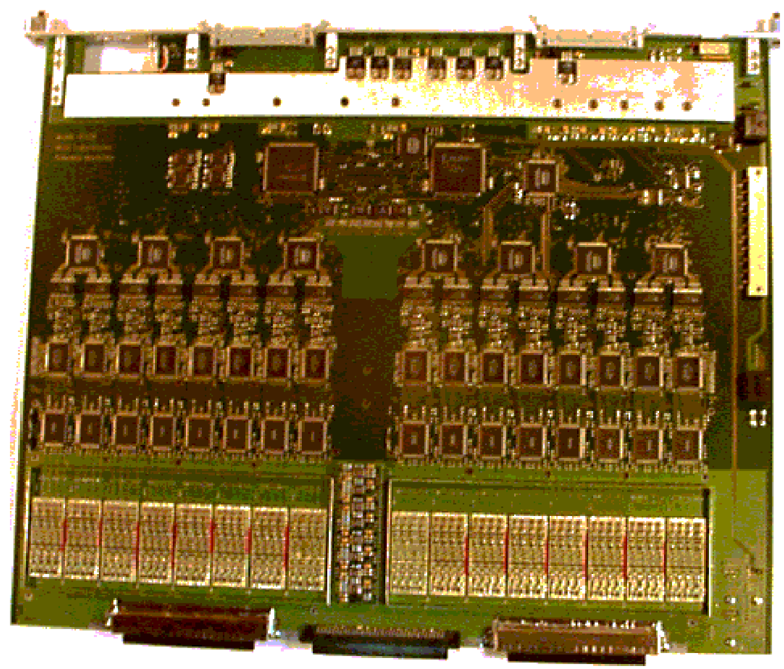
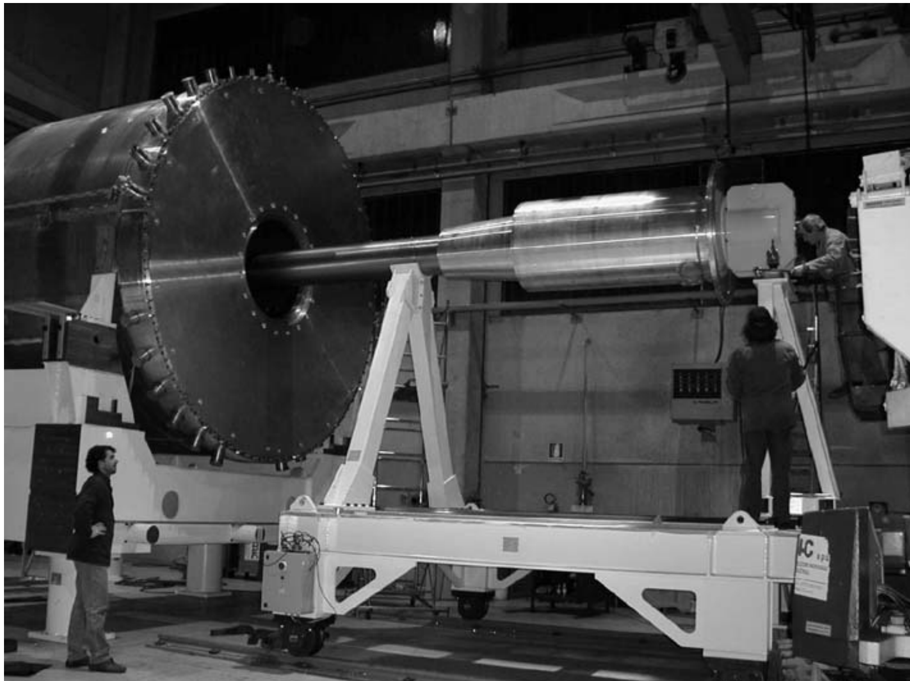
CRPP
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York



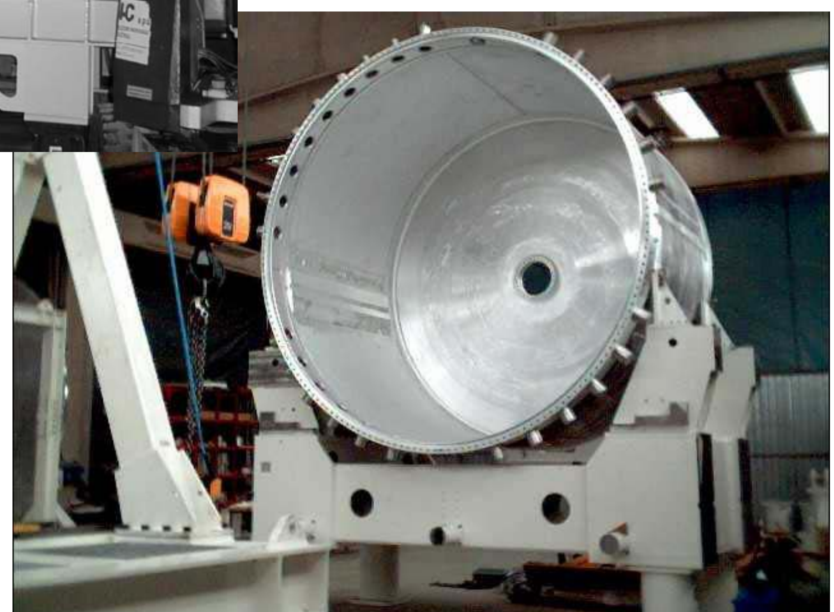
ATLAS LAr electronic frontend board

Canada and ATLAS in pictures



testing the insertion of the FCAL in the endcap cryostat

Alberta
Carleton
CRPP
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York



view of the endcap cryostat and feedthrough ports

LHC PP Cross Section

ATLAS

Multi-purpose pp detector designed to exploit the full discovery potential of the LHC

Designed to operate at high luminosity

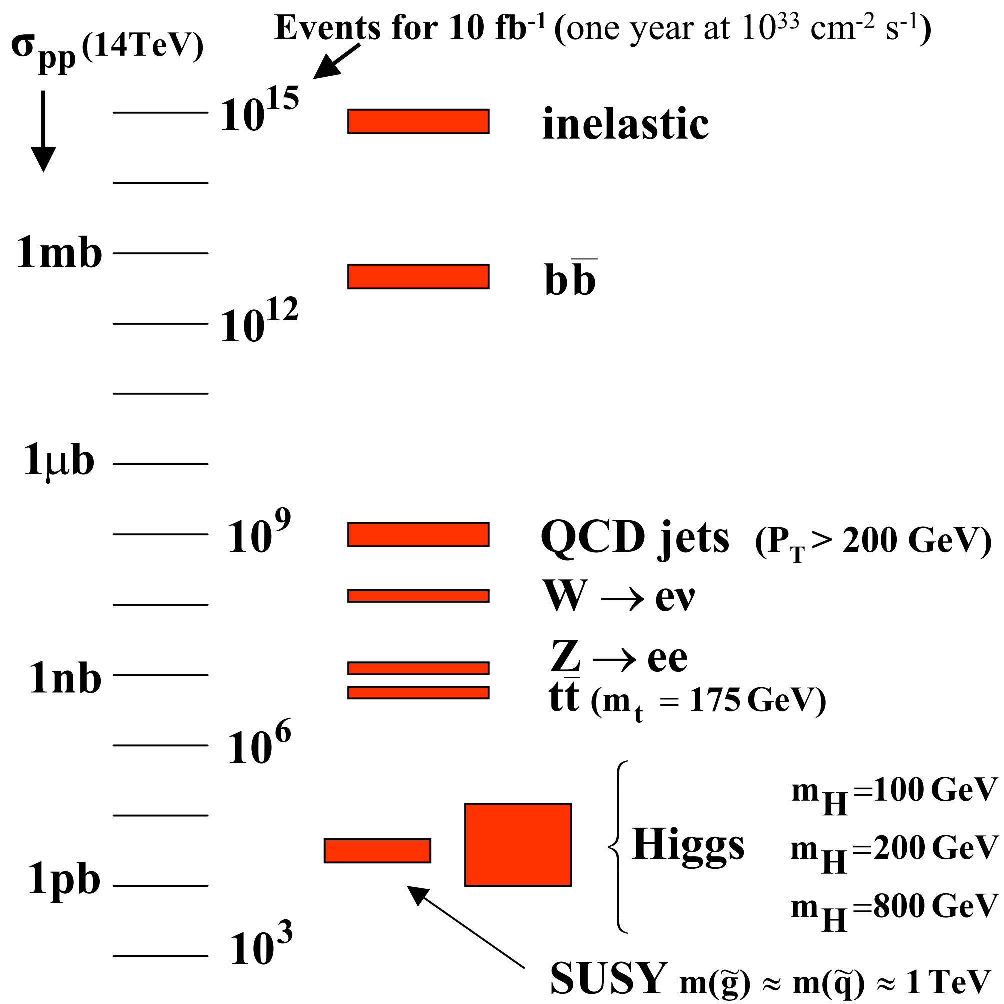
$$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

and at initial lower luminosities

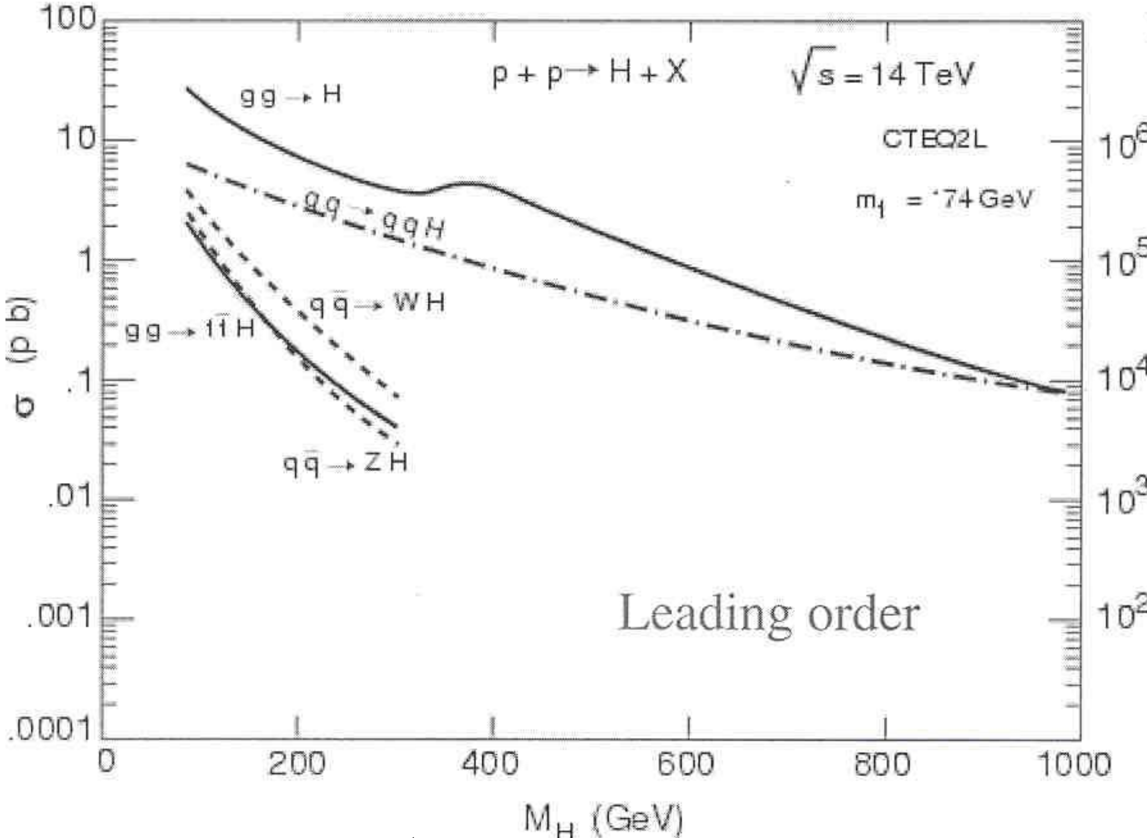
Designed to be sensitive to many signatures

$$e, \gamma, \mu, \text{jet}, E_T^{\text{miss}}, \text{b-tagging},\ldots$$

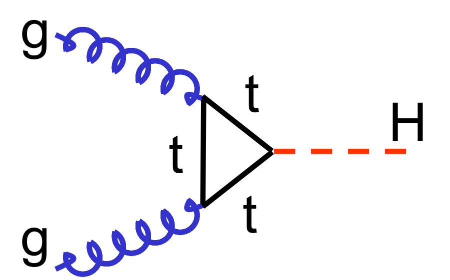
and to more complex signatures, like top and heavy flavour from secondary vertices

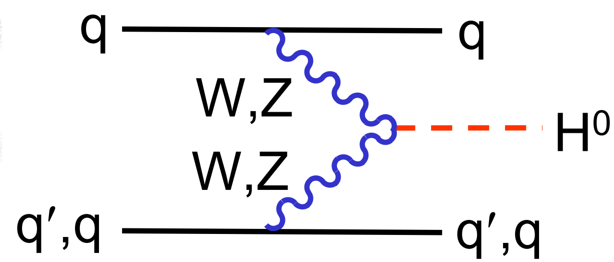


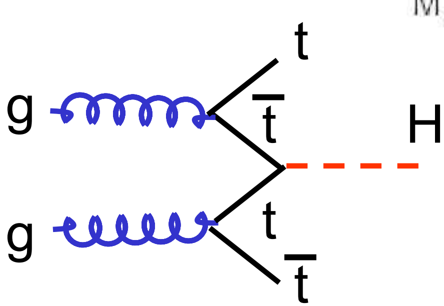
SM Higgs Production at the LHC

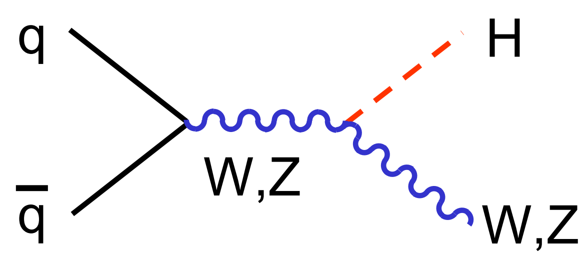


Events for
100 fb^{-1} (one year at 10^{34} cm^{-2} s^{-1})









Main SM Higgs Search Channels

Large QCD backgrounds:

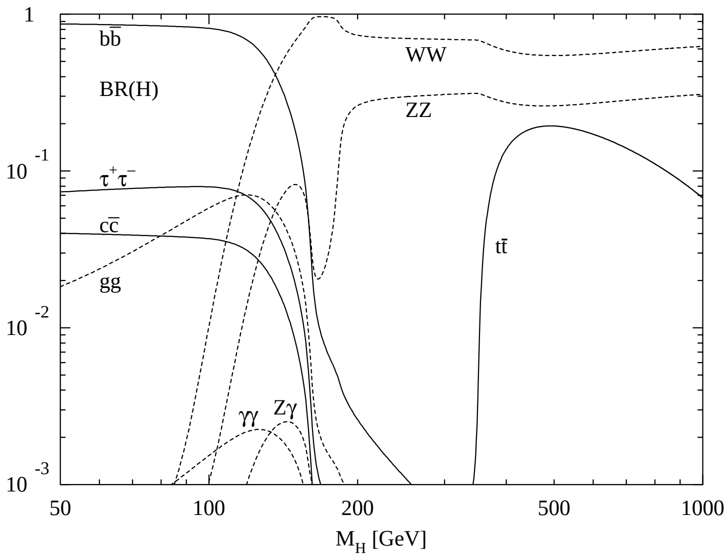
$$\sigma\left(H \to b\bar{b}\right) \approx 20\ \text{pb}$$
$$\sigma\left(b\bar{b}\right) \approx 500\ \mu\text{b}$$

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!**

$H \to ZZ \to l\,l\,\nu\,\nu$

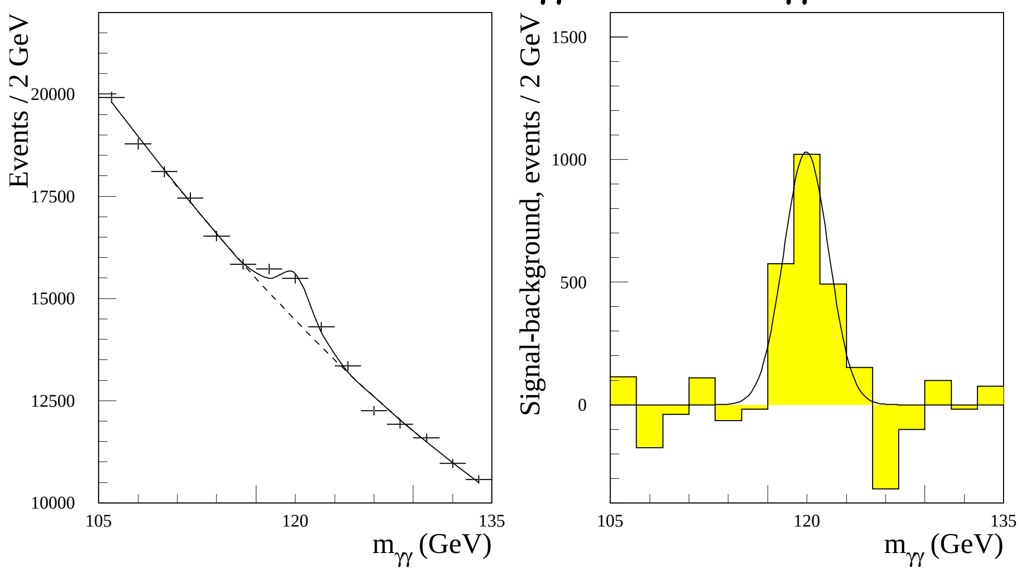
$H \to ZZ \to l\,l\,j\,j$

$H \to WW \to l\,\nu\,j\,j$

***M_H* > 300 GeV**
forward jet tag

$H \to \gamma\gamma$ at ATLAS

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



Analysis:

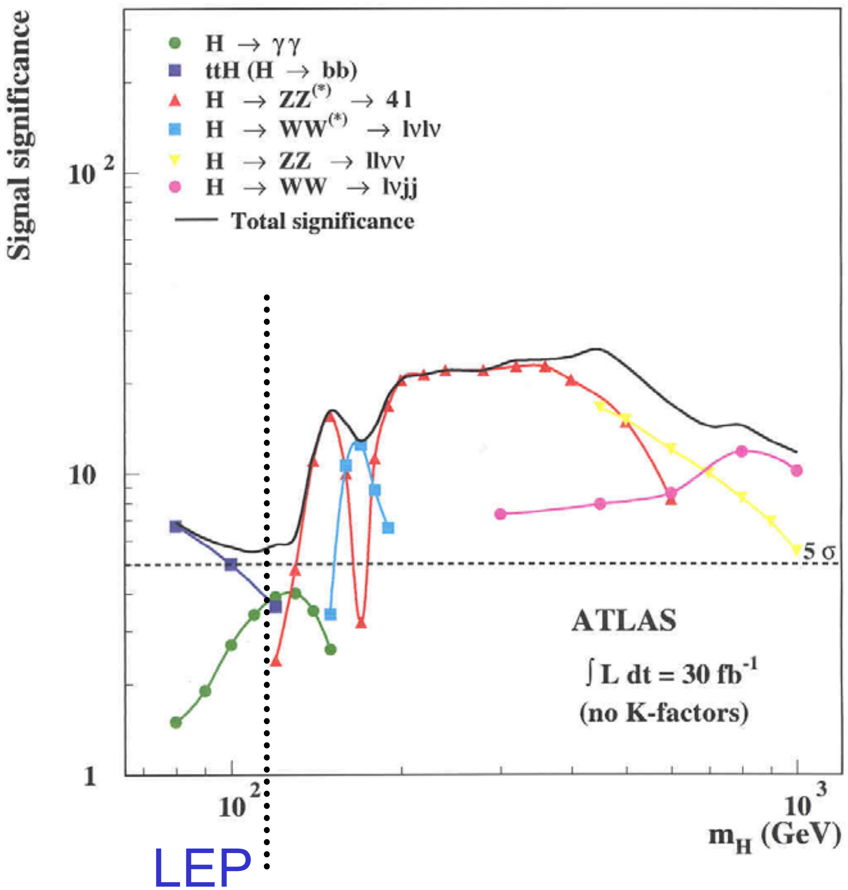
Two isolated γ's: $p_T^1 > 40$ GeV, $p_T^2 > 25$ GeV, $|\eta| < 2.5$

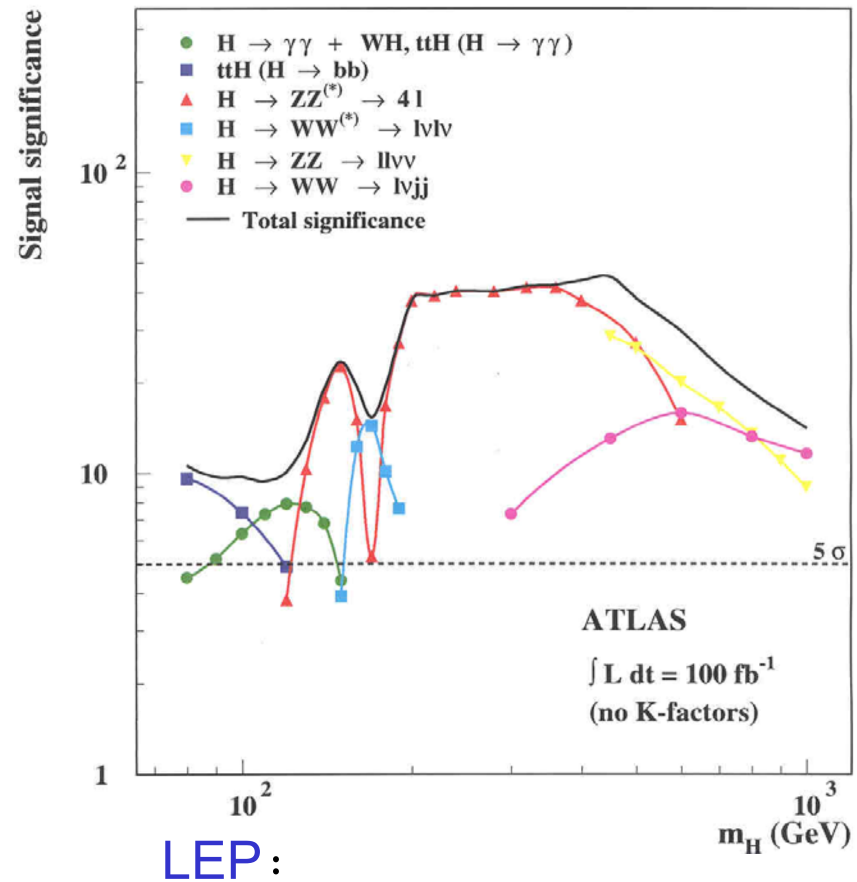
Good γ/jet separation: QCD jet background at the level of 10 to 20% of the irreducible $\gamma\gamma$ background

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

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

ATLAS SM Higgs Discovery Potential



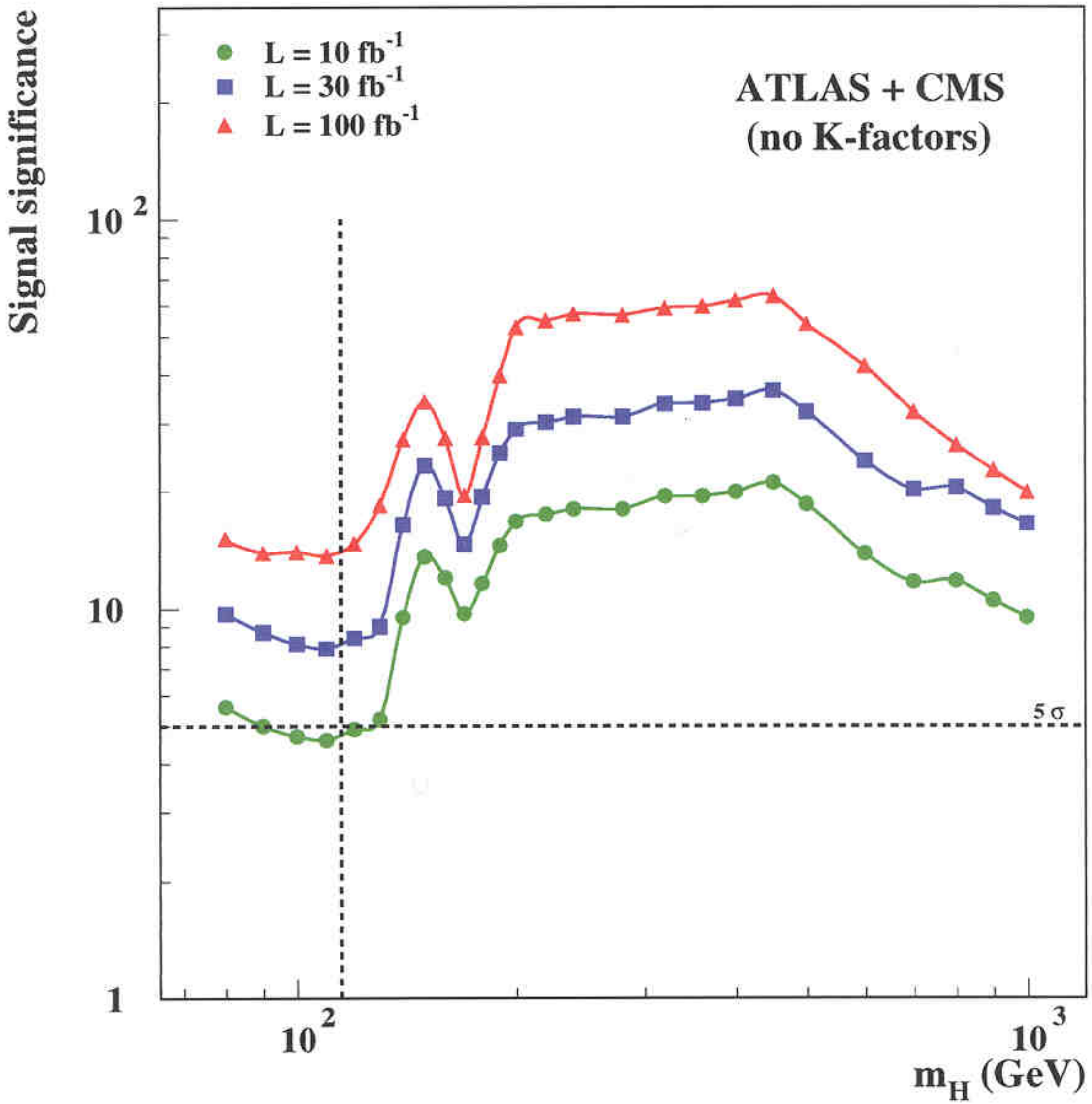


SM Higgs can be discovered over full mass range with 30 fb^{-1}

In most cases, more than one channel is available.

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

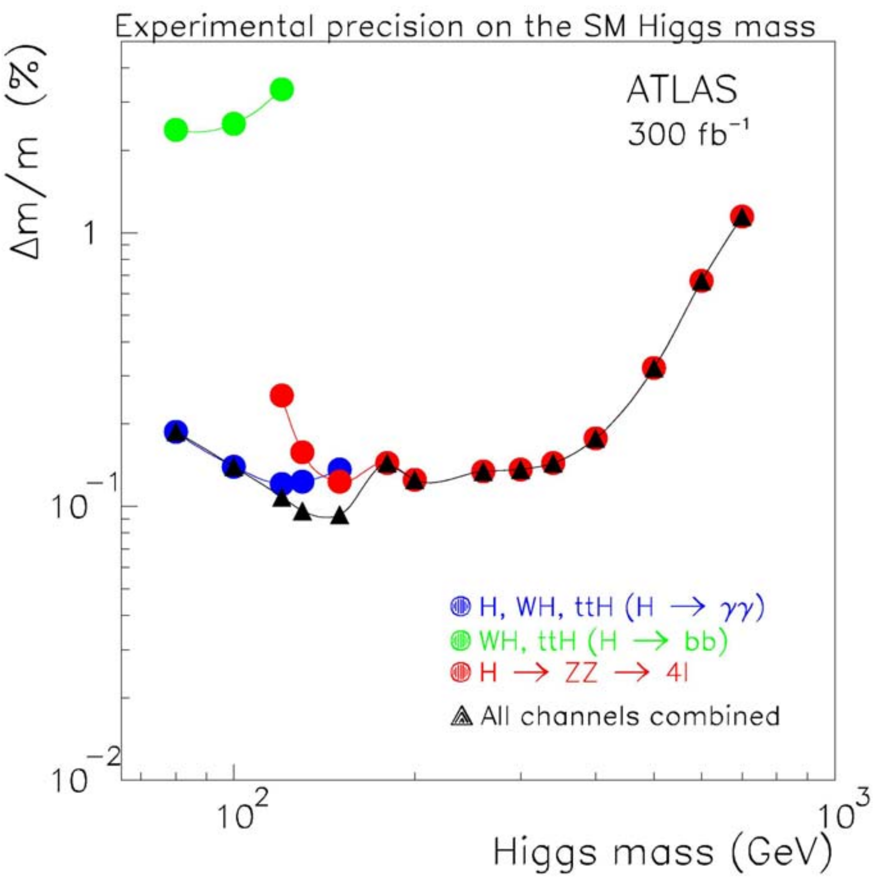
LHC SM Higgs Discovery Potential

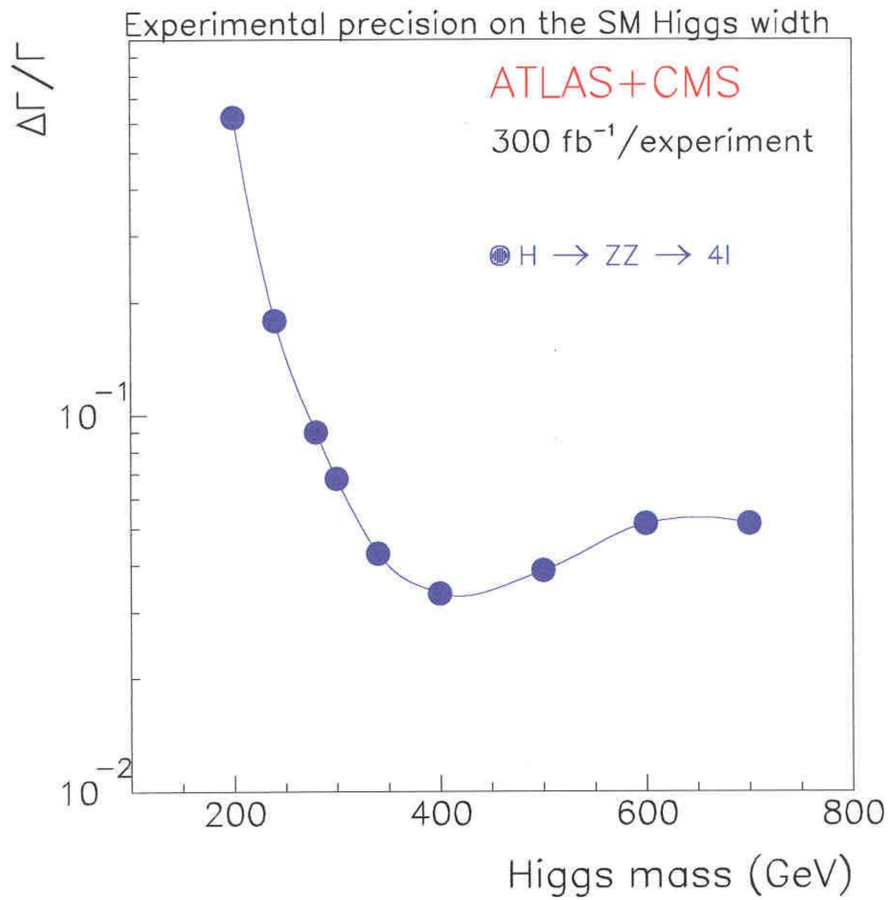


need 10 fb^{-1} for 5σ 115 GeV Higgs discovery (during 2007?)

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 Λ >> 1 TeV, need "unnatural" tuning

Beware… what seems unnatural today...

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

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

Violation of naturalness = hierachy problem

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

Not the only way out… extra dimensions!

Supersymmetry

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

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

	CP odd	CP even														
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 parameters only (in "constrained MSSM")

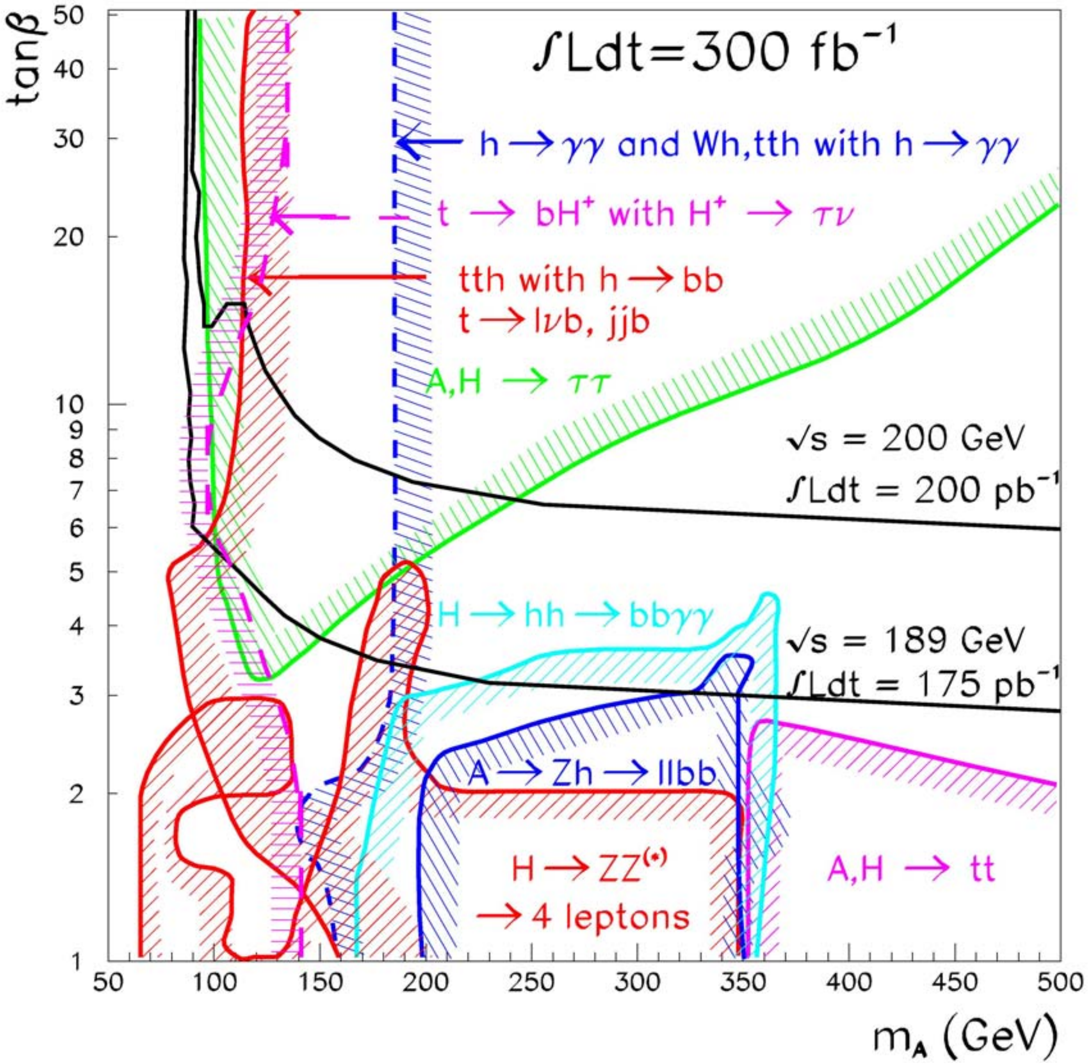
$$m_A \qquad \text{and} \qquad \tan\beta = \frac{\text{vev } H_u}{\text{vev } H_d}$$

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

ATLAS MSSM Higgs Search

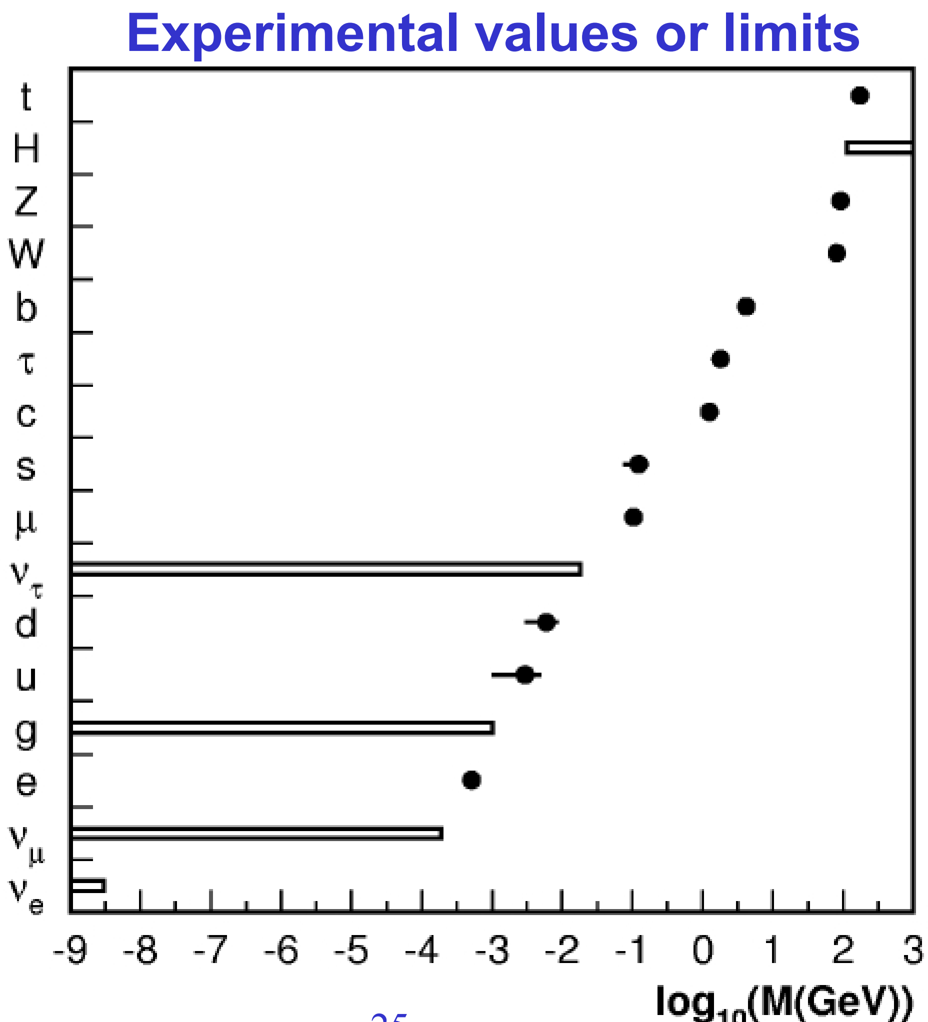


Full parameter space covered, SM and MSSM can be distinguished for almost all cases

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

Discovery of heavy Higgses (m_A > 500 GeV) seem to be difficult (top modes)

Fundamental Mass Values



$\leftarrow \; m_\gamma < 2\times 10^{-25}$ 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

Mass without mass?

The SM Higgs sector still requires direct experimental verification

Origin of electroweak symmetry hiding
Origin of mass

LEP results tantalizing

$M_{\mathrm{H}} \approx 116\ \mathrm{GeV}$ if signal hypothesis valid… $\approx 2\sigma$

$M_{\mathrm{H}} > 114\ \mathrm{GeV}\ @95\%\ \mathrm{CL}$

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**

Strong Canadian participation in ATLAS

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

This is going to be a very exciting decade !