Higgs Physics

Lecture 2

Experimental Aspects

ÉCOLE DE PHYSIQUE
LES HOUCHES

Electroweak Precision Data Indirect Constraints

The LEP and SLC legacies

Experimental Constraint : Electroweak Precision Data and the Higgs Mass

As Prof. Kawamoto pointed out in his lecture :

The standard model has 3 free parameters (3 again…) not counting the Higgs mass and the fermion masses and couplings.

Particularly useful set is :

1.- The fine structure constant : $\alpha = 1/137.035999679(94)$ $\boxed{10^{-9}}$

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

2.- The Fermi constant : $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ $\boxed{10^{-5}}$

Determined from muon lifetime

3.- The Z mass : $M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ $\boxed{10^{-5}}$

Measured from the Z lineshape scan at LEP

Experimental Constraint : Electroweak Precision Data and the Higgs Mass

Taking the hypothesis of a Minimal Standard Model, the radiative corrections to numerous observables can be computed in order to assess the impact of certain particles e.g. the Higgs boson

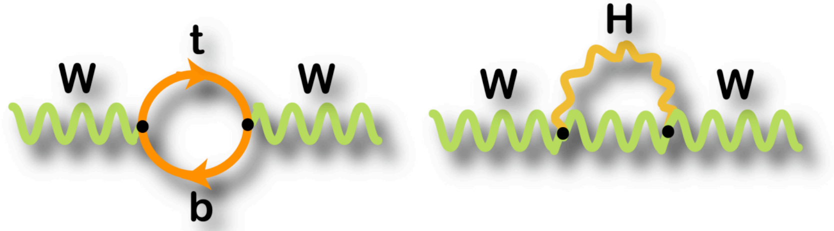
From the measurement of these observables a constraint is derived

For example the corrections to the Fermi coupling constant can be written as :

$$G_F = \frac{\pi \alpha_{QED}}{\sqrt{2} m_W^2 (1 - m_W^2/m_Z^2)}(1 + \Delta r)$$

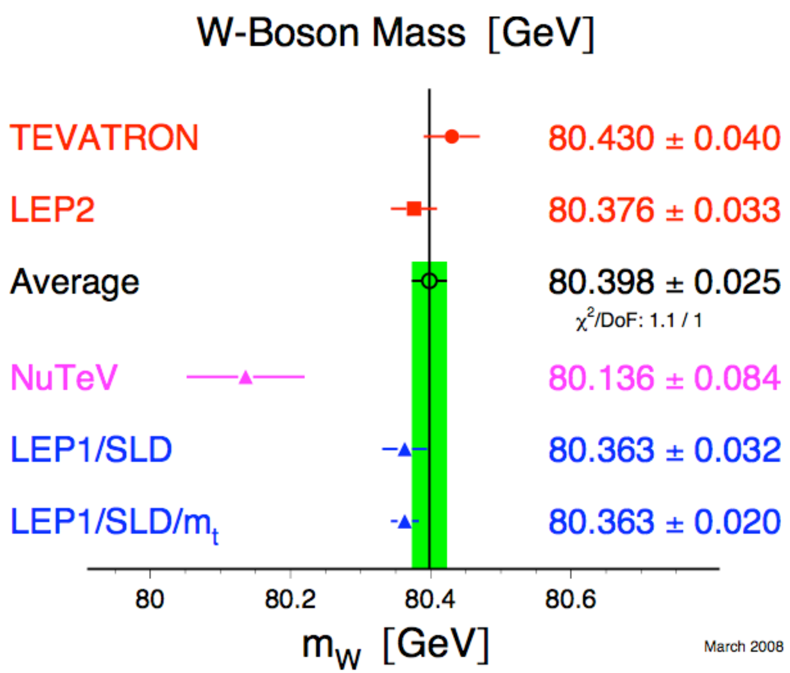
With :

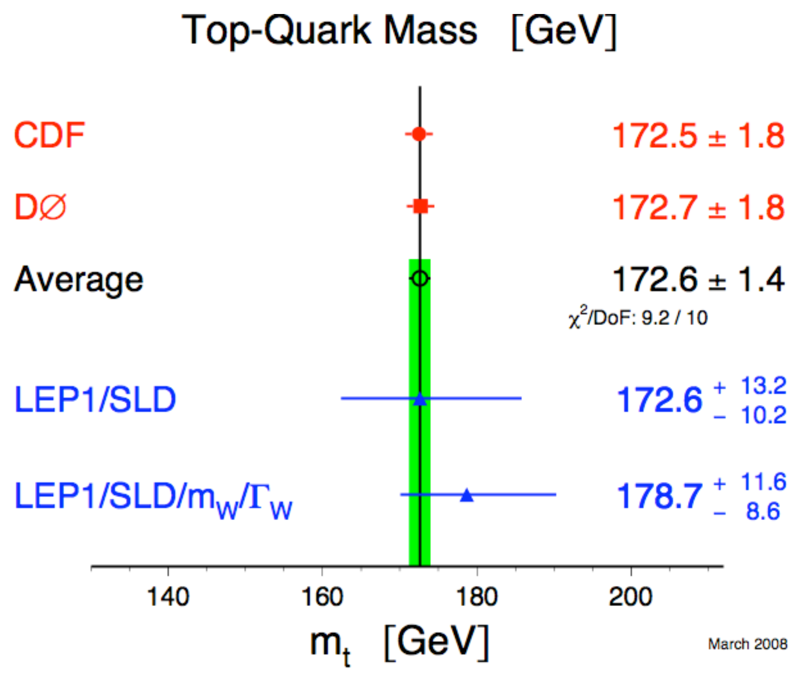
$$\begin{cases} \Delta r_t \propto m_t^2 \\ \underline{\Delta r_H \propto \log(m_H/m_W)} \end{cases}$$



Essential ingredients top, W and Z masses and α_{QED}

W and Top quark mass measurements





Precision of ~0.03%

Precision of ~0.8%

-TeVatron should outperform LEP2 soon maybe ~25 MeV

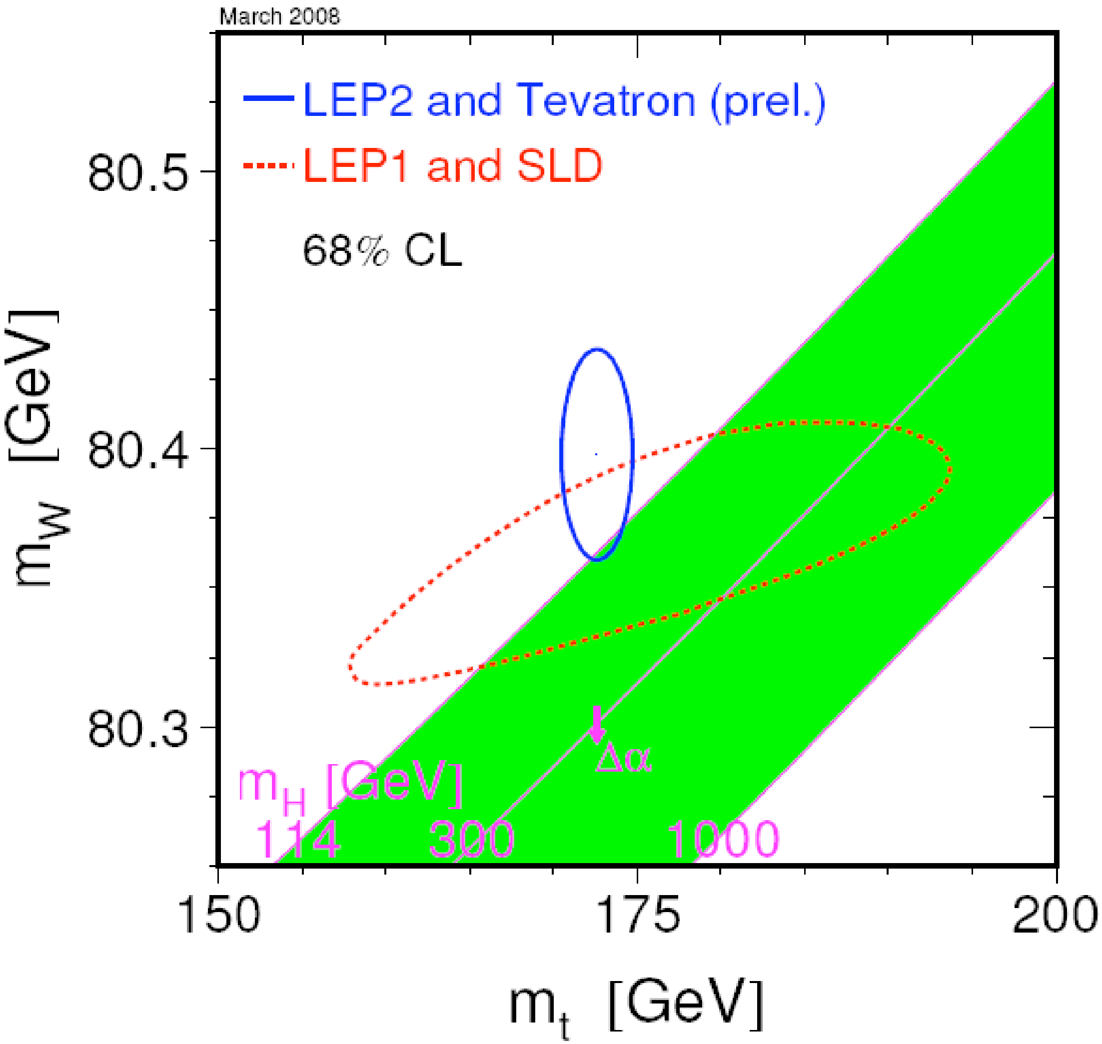
- LHC should outperform TeVatron but not very soon ~15 MeV

-TeVatron is aiming at ~ 1 GeV

- LHC should outperform TeVatron but not so soon either

Separating and thus comparing direct and indirect measurements of m_W and m_{top}

VIP (Very Important Plot)



- Direct and Indirect overlap

- W mass consistent

- Predicted top mass in perfect agreement :

$$m_t = 174.7^{+10.0}_{-7.8}\ \mathrm{GeV}$$

(all data)

- Direct measurements clearly prefer low Higgs masses (like MSSM)

- What is the origin of $\Delta\alpha$?

The Electromagnetic Coupling Constant

$$\alpha_{QED}(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(m_Z^2) - \Delta\alpha_{had}(m_Z^2) - \Delta\alpha_{top}(m_Z^2)}$$

As mentionned above $\alpha(0)$ measured with ~10^{-9} precision

The probem is how to evaluate : $\Delta\alpha_{had}(m_Z^2)$

The origin of one of the mot important uncertainties on the Higgs mass prediction :

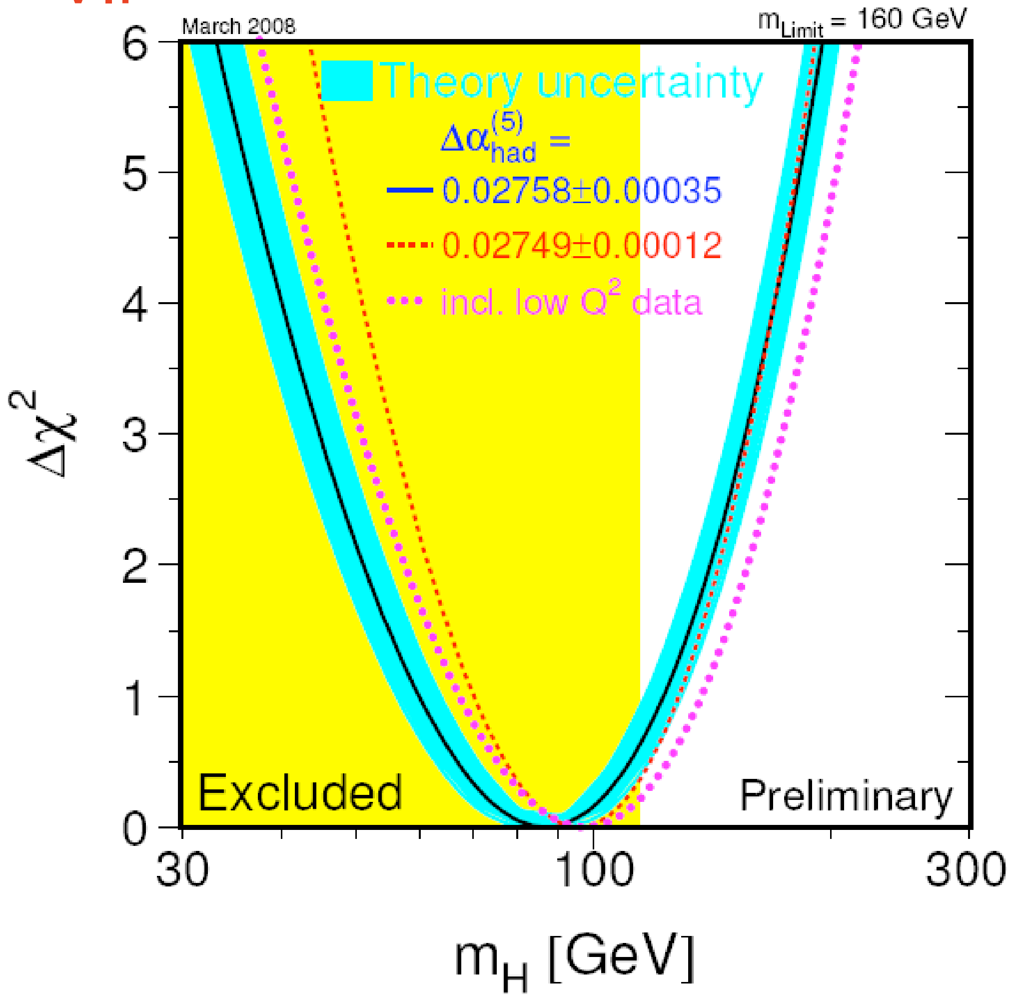
The famous blue band plot is named after this contribution

The Famous Blue Band Plot

Comparing direct search to indirect measurement

Using all available precision measurements a global fit of the most likely Higgs Boson mass is performed

VIP



- The yellow band is LEP 95% CL exclusion (but there is more information than just a band)

- The fit yields :

$$M_H = 77^{+28}_{-22}\ \text{GeV}$$

- The 90% Confidence Interval :

$$42\ \text{GeV} \leq M_H \leq 124\ \text{GeV}$$

- Including LEP limit :

$$M_H \leq 167\ (155,\ 195)\ \text{GeV}$$

at $95\ (90,\ 99)\%\ \text{CL}$

The Complete Data

PDG

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	$170.9 \pm 1.8 \pm 0.6$	171.1 ± 1.9	-0.1	-0.8
M_W [GeV]	80.428 ± 0.039	80.375 ± 0.015	1.4	1.7
	80.376 ± 0.033		0.0	0.5
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	-0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0010	-0.7	-0.5
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	–	–
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.59 ± 0.08	–	–
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.988 ± 0.016	–	–
σ_{had} [nb]	41.541 ± 0.037	41.466 ± 0.009	2.0	2.0
R_e	20.804 ± 0.050	20.758 ± 0.011	0.9	1.0
R_μ	20.785 ± 0.033	20.758 ± 0.011	0.8	0.9
R_τ	20.764 ± 0.045	20.803 ± 0.011	-0.9	-0.8
R_b	0.21629 ± 0.00066	0.21584 ± 0.00006	0.7	0.7
R_c	0.1721 ± 0.0030	0.17228 ± 0.00004	-0.1	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01627 ± 0.00023	-0.7	-0.6
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5	0.7
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1033 ± 0.0007	-2.5	-2.0
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0738 ± 0.0006	-0.9	-0.7
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1034 ± 0.0007	-0.5	-0.4
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23149 ± 0.00013	0.8	0.6
	0.2238 ± 0.0050		-1.5	-1.6
A_e	0.15138 ± 0.00216	0.1473 ± 0.0011	1.9	2.4
	0.1544 ± 0.0060		1.2	1.4
	0.1498 ± 0.0049		0.5	0.7
A_μ	0.142 ± 0.015		-0.4	-0.3
A_τ	0.136 ± 0.015		-0.8	-0.7
	0.1439 ± 0.0043		-0.8	-0.5
A_b	0.923 ± 0.020	0.9348 ± 0.0001	-0.6	-0.6
A_c	0.670 ± 0.027	0.6679 ± 0.0005	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4	-0.4
g_L^2	0.3010 ± 0.0015	0.30386 ± 0.00018	-1.9	-1.8
g_R^2	0.0308 ± 0.0011	0.03001 ± 0.00003	0.7	0.7
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
A_{PV}	$(-1.31 \pm 0.17)\cdot 10^{-7}$	$(-1.54 \pm 0.02)\cdot 10^{-7}$	1.3	1.2
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.16 ± 0.03	1.2	1.2
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.76 ± 0.04	0.1	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$\left(3.55^{+0.53}_{-0.46}\right)\cdot 10^{-3}$	$(3.19 \pm 0.08)\cdot 10^{-3}$	0.8	0.7
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$4511.07(74)\cdot 10^{-9}$	$4509.08(10)\cdot 10^{-9}$	2.7	2.7
τ_τ [fs]	290.93 ± 0.48	291.80 ± 1.76	-0.4	-0.4

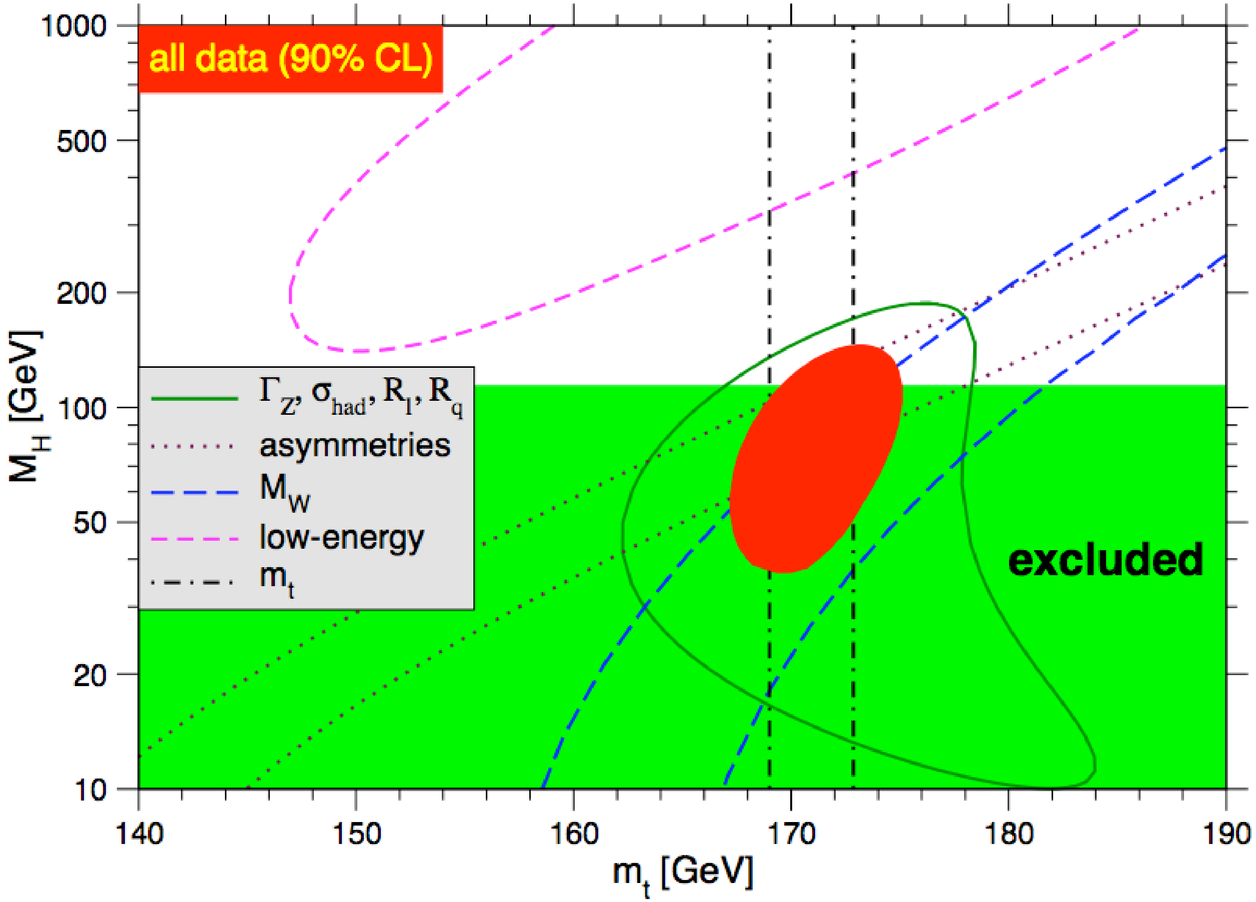
July 24, 2008 18:04

- Numerous observables
- Numerous experiments (with different systematics)
- Within experiments numerous analyses (with different systematics)
- Various theoretical inputs

But still the Standard Model is defined by 3 parameters

Electroweak Precision Data and the Higgs Mass

Global Picture



- Results overwhelmingly point to a low Higgs Boson mass
- Still a small tension with A_{FB}^b and NuTeV results

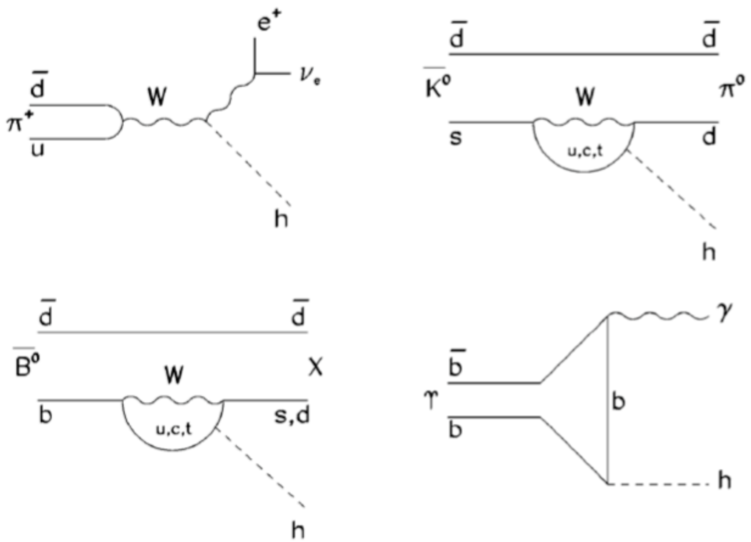
The Non Perturbative Regime

Prehistory of Higgs Boson Searches

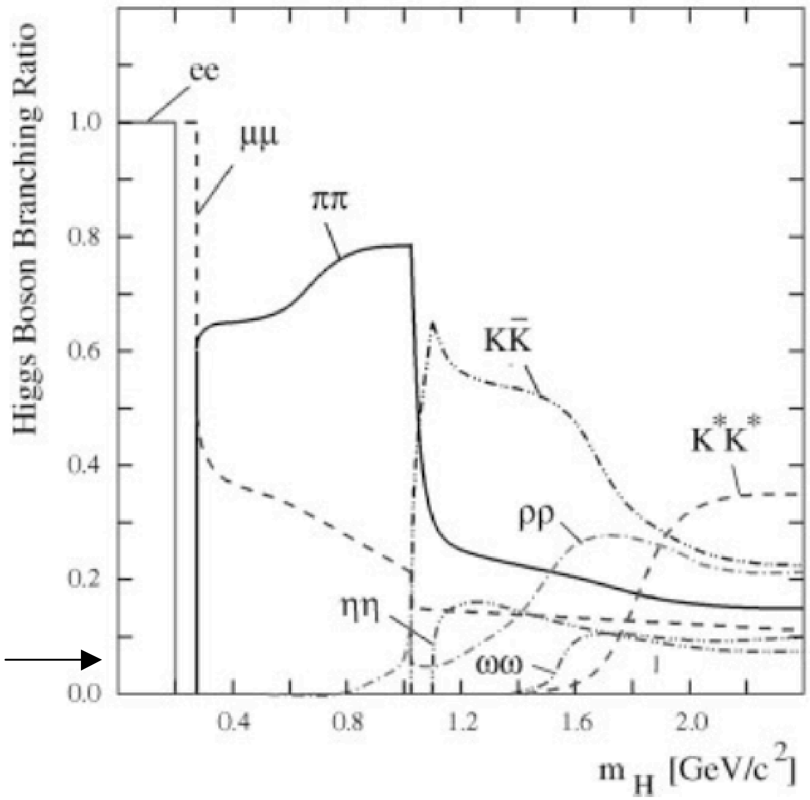
The situation before LEP

The non-perturbative regime

Production processes



Branching fractions



Below e^+e^- threshold search for $\gamma\gamma$ →

Higgs boson under 5 GeV is very unlikely

Only unlikely due to the large uncertainties in the decay and production mechanisms a such low energies

The Perturbative Regime

Slightly beyond the rule of thumbs…

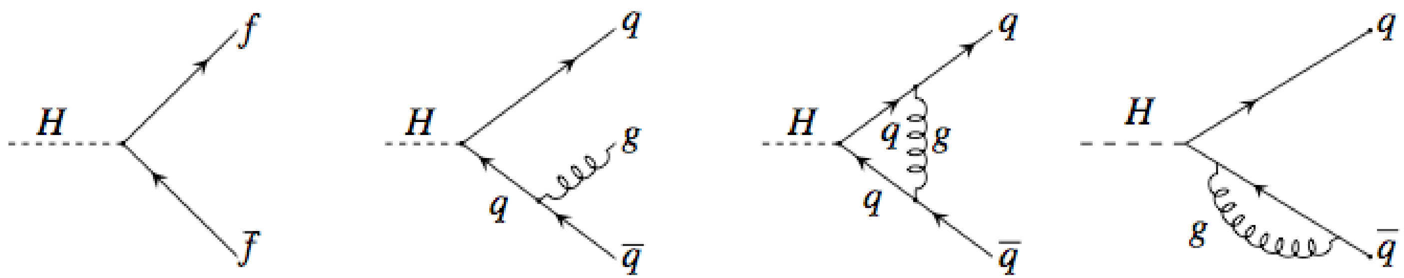
$$\underbrace{g_{Hf\bar{f}} = \frac{m_f}{v}}_{\text{Fermion coupling}} \qquad \underbrace{g_{HVV} = \frac{2m_V^2}{v}}_{\text{IVB coupling}}$$

Main Decay Modes

- Fermions :

$$\Gamma_{\mathrm{Born}}(\mathrm{H} \to \mathrm{f}\bar{\mathrm{f}}) = \frac{G_F N_c}{4\sqrt{2}\pi} m_{\mathrm{H}} m_{\mathrm{f}}^2 \beta_f^3 = \frac{g^2 N_c}{32\pi m_{\mathrm{W}}^2} m_{\mathrm{H}} m_{\mathrm{f}}^2 \beta_f^3$$

$$\beta_f = \sqrt{1 - 4m_{\mathrm{f}}^2/m_{\mathrm{H}}^2}$$



- When fermions are quarks NLO corrections are important

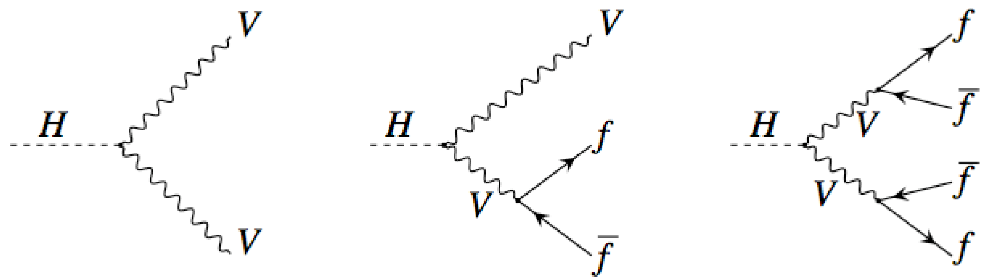
- Below the tt and above the bb thresholds : bb is dominant

- One specificity is the H decay to tt* to tbW right below the tt threshold (accounts for 2% of the branching in that region)

- Vector Bosons (W and Z) :

$$\Gamma(\mathrm{H}\to \mathrm{VV}) = \frac{G_F m_{\mathrm{H}}^3}{16\sqrt{2}\pi}\delta_{\mathrm{V}}\sqrt{1-4x}(1-4x+12x^2)$$

Where : $x = m_{\mathrm{V}}^2/m_{\mathrm{H}}^2,\ \delta_{\mathrm{W}} = 2$ and $\delta_{\mathrm{Z}} = 1$

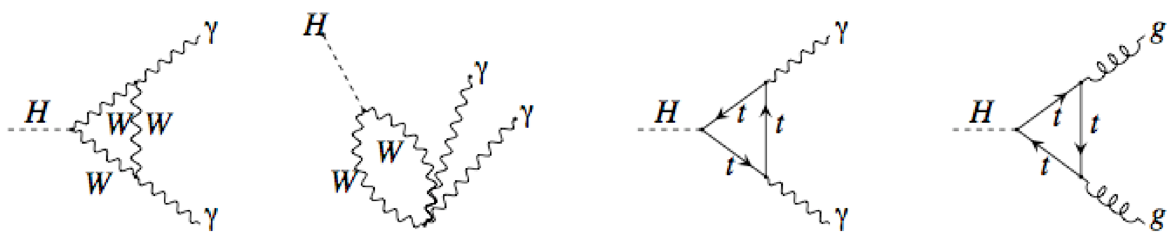


The total width grows as m_h^3 this will have a large impact on the total width of the Higgs boson

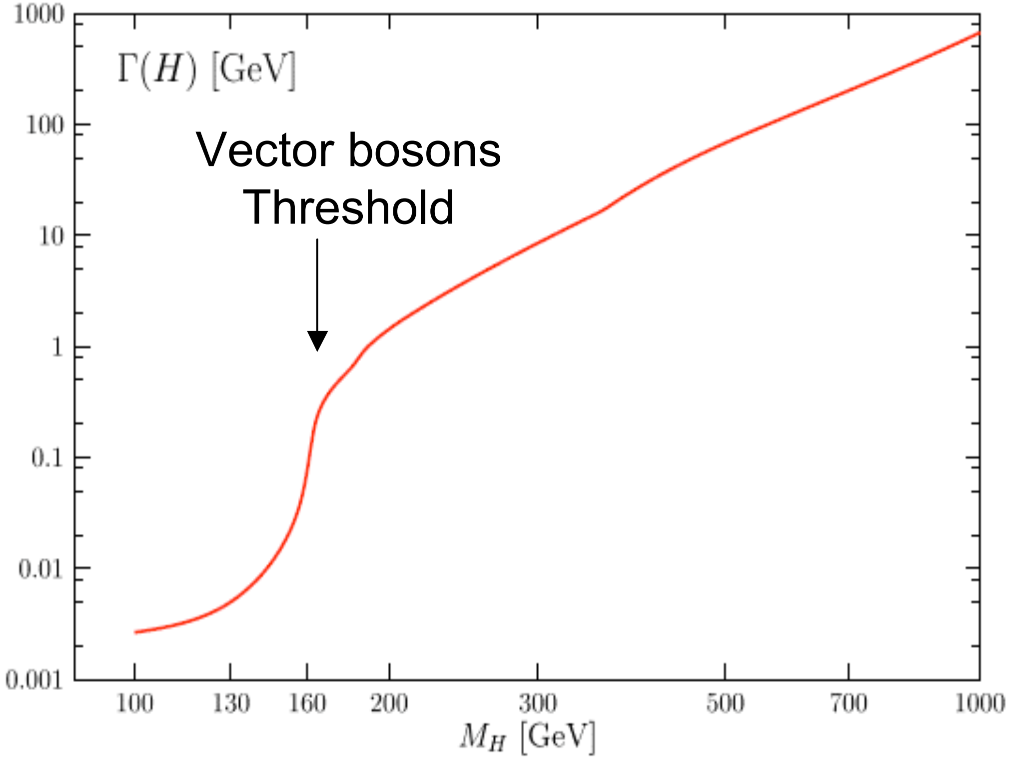
- Photons :

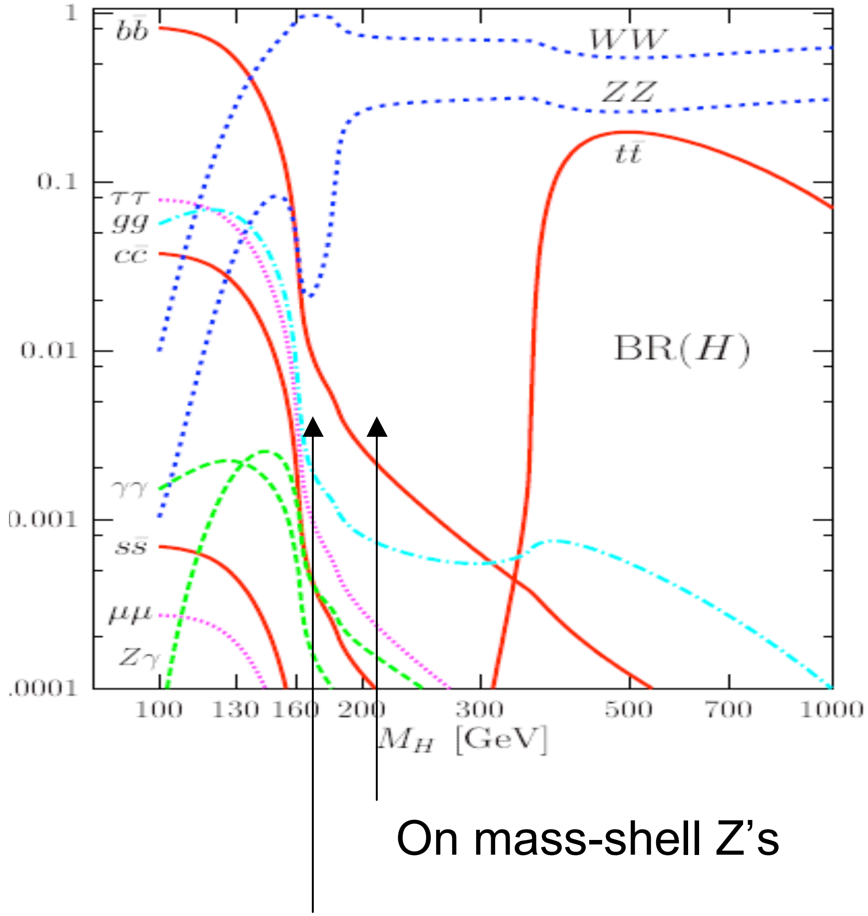
$$\Gamma(\mathrm{H}\to\gamma\gamma) = \frac{G_F\alpha^2 m_{\mathrm{H}}^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 \underbrace{A_{1/2}^H(\tau_f) + A_1^H(\tau_W)}_{\text{Form factors}}\right|^2$$

Dominant contribution



The Higgs Boson Total Width and Branching Fractions





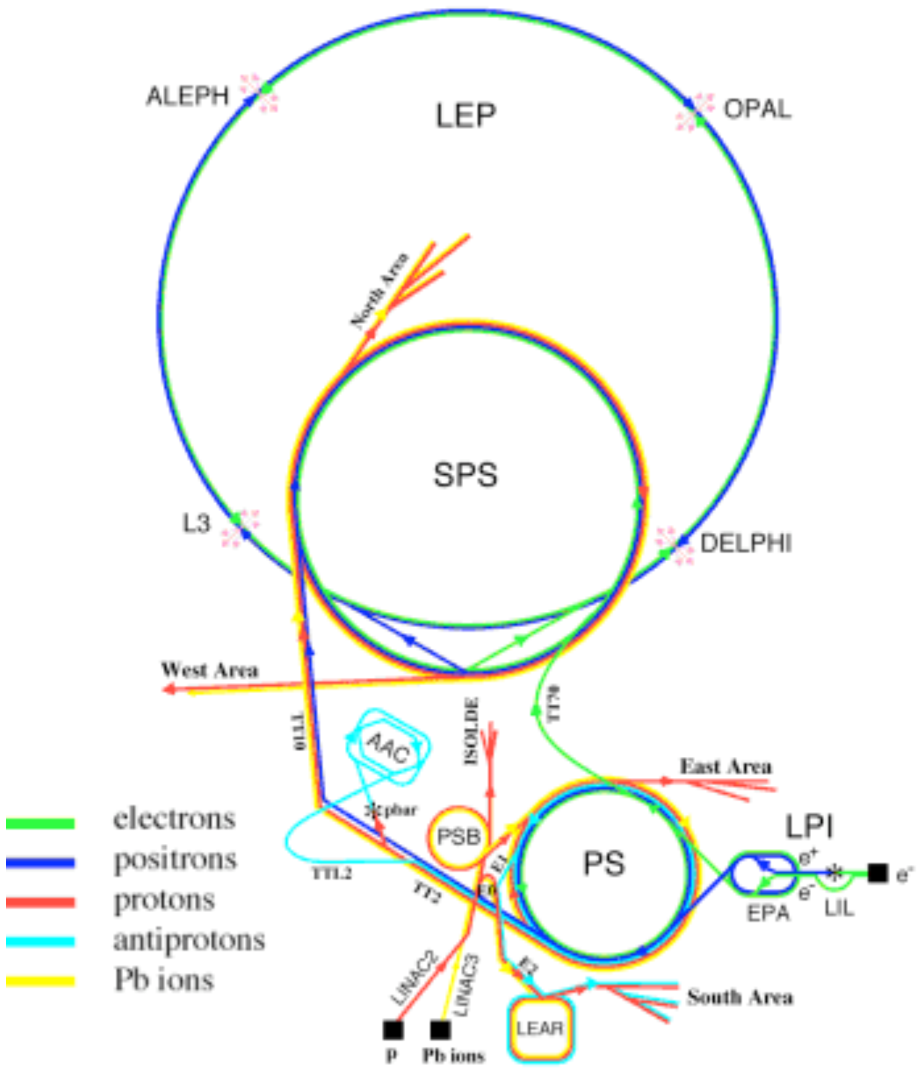
Commonalities :

- bb dominant at low masses
- WW and ZZ dominant at high masses

The LEP Legacy

History of Higgs Boson Searches

First LEP Legacy : The LEP Machine



e^+e^- collider

Scanned the Z lineshape from 1989 to 1994

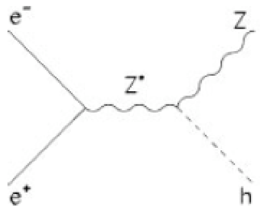
LEP 1

Since 1995 started taking data at higher energies

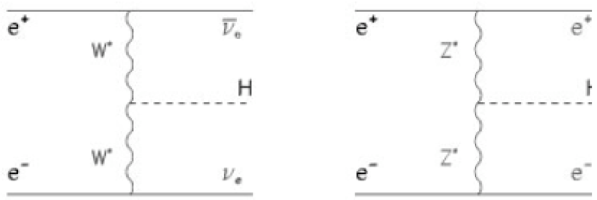
… up to 209 GeV…

LEP 2

Production Processes and Topologies

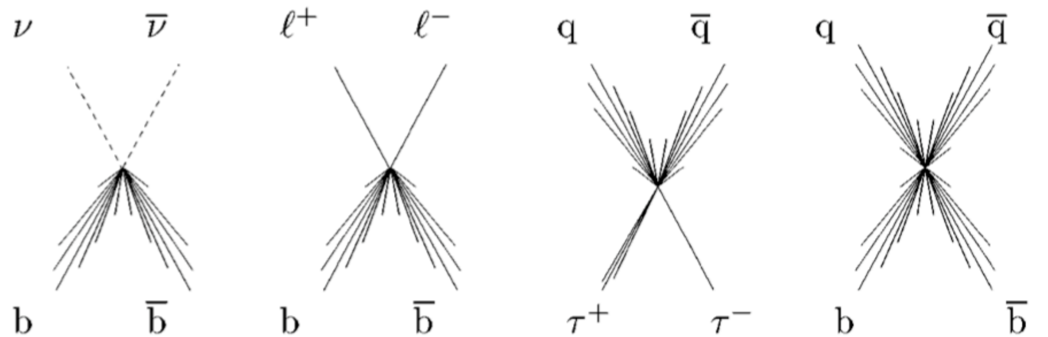


Higgs-Strahlung

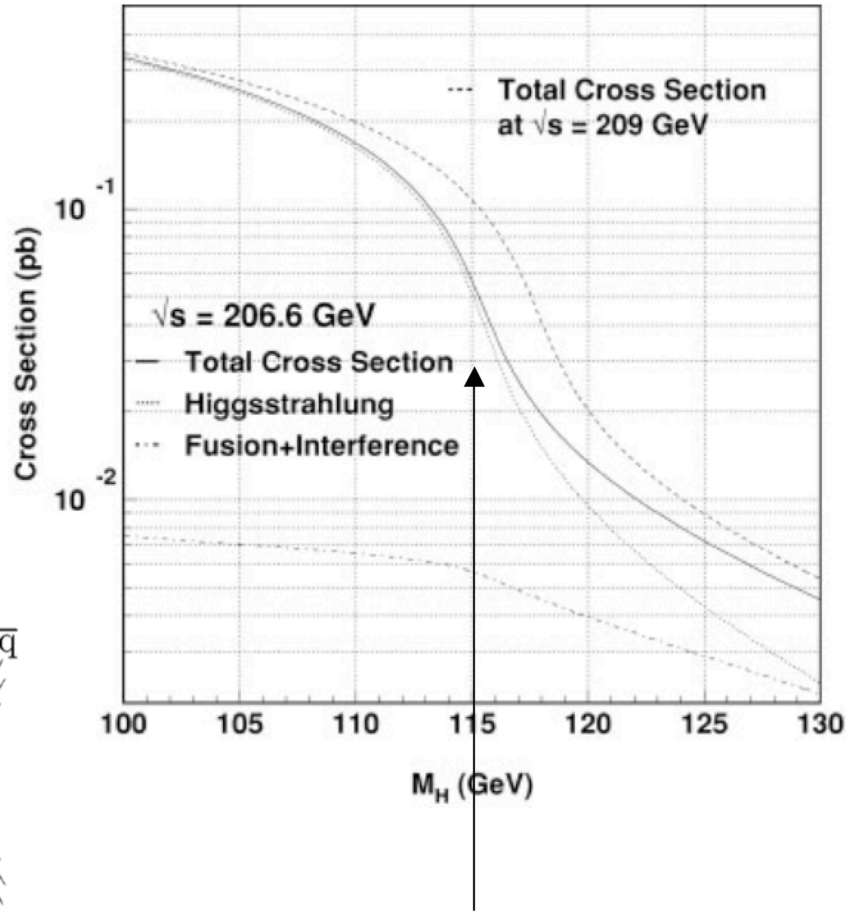


Vector Boson Fusion

Thus with a Higgs boson decaying to bb :

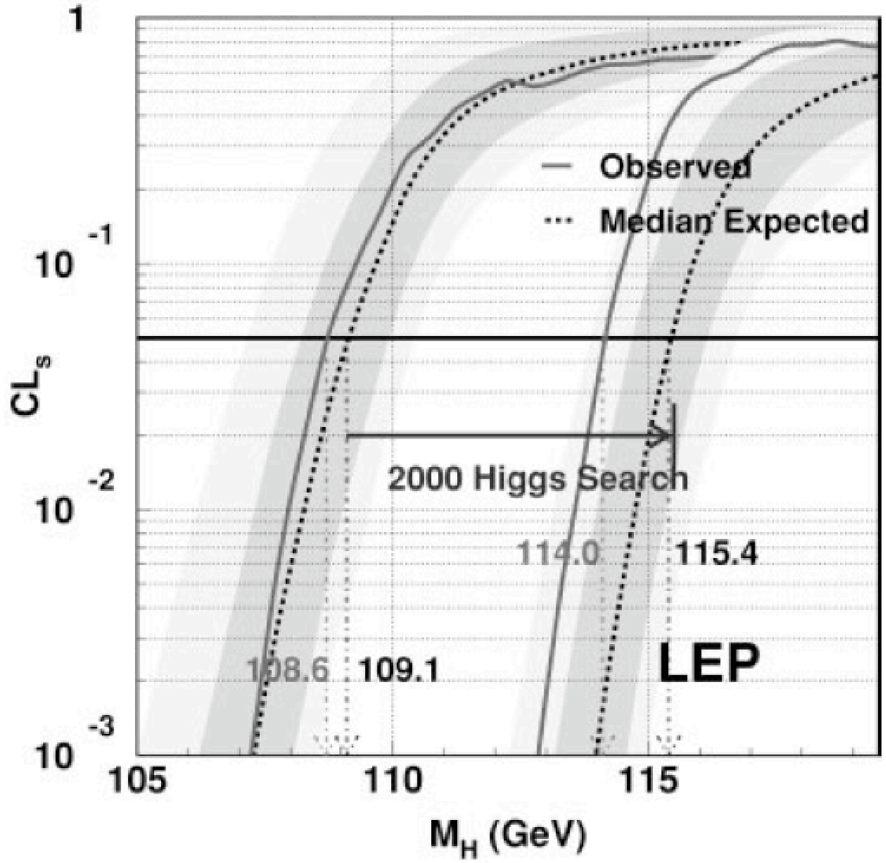


Single most powerful channel



Steep threshold

Second LEP legacy : Lower Limit on the Higgs Boson Mass

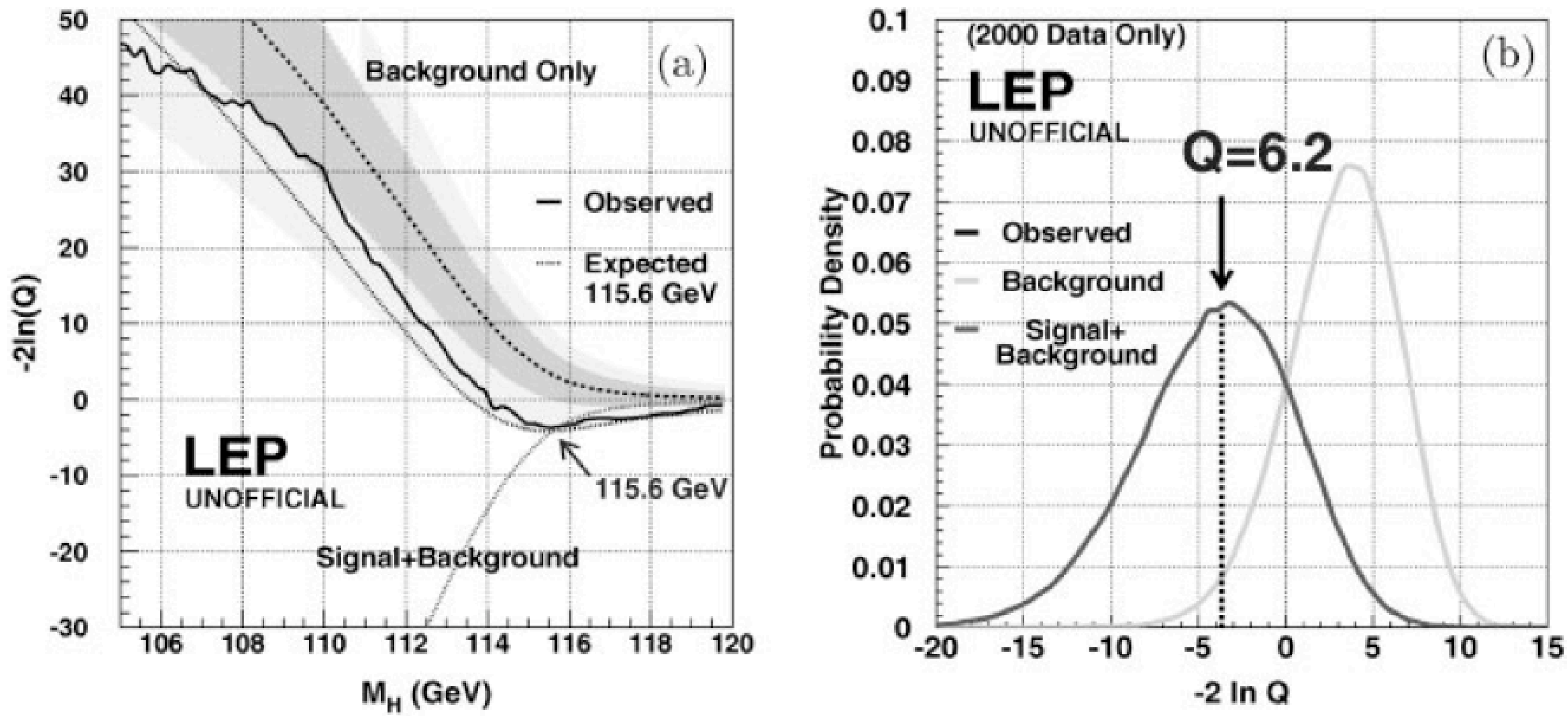


Higgs boson mass > 114 GeV at 95% CL

…but expected to exculde 115.4 GeV

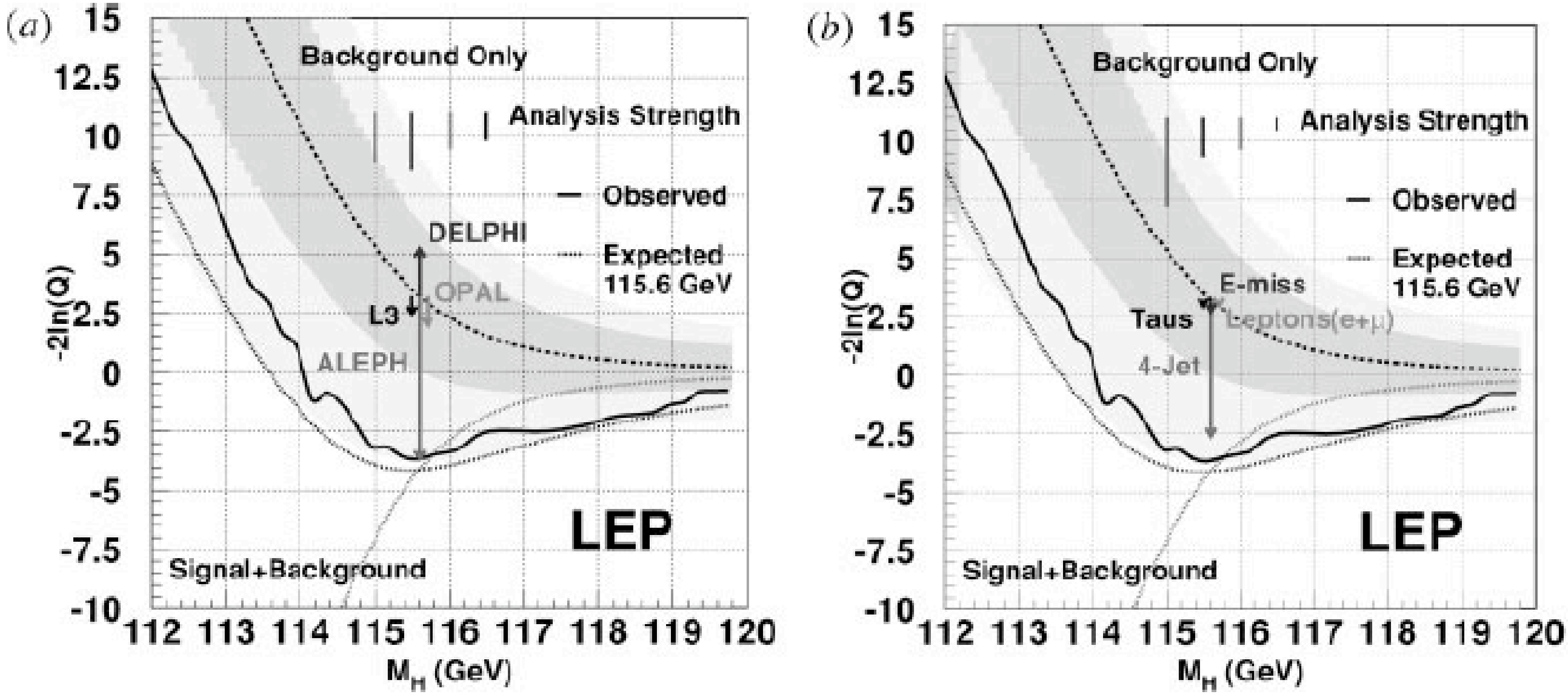
Third LEP Legacy : The Hint

$$-2\ln Q = 2 \cdot s_{\text{tot}} - 2 \cdot \sum n_i \ln\left(1 + \frac{s_i}{b_i}\right)$$



Combined observation consistent with a signal but less than 2σ deviation from background

Consistency Checks

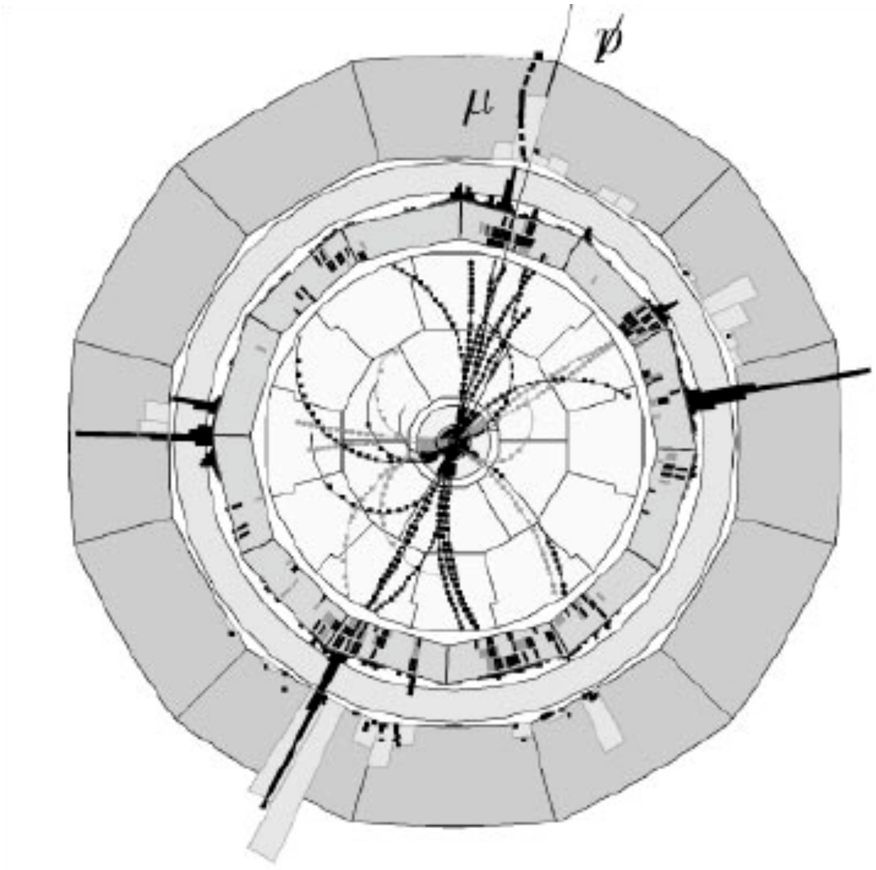


- Most of the Excess was in the most powerful channel 4-jets
- Most of the Excess was in one experiment : ALEPH
- Results are perfectly consistent with a Higgs boson production…

…but the significance is small

Latest results (after various data re-processings) have slightly changed : limit 114.4 GeV/c^2 and the significance of the excess slightly lower

Puzzling Hint



Single most significant event seen by ALEPH in the most significant analysis channel

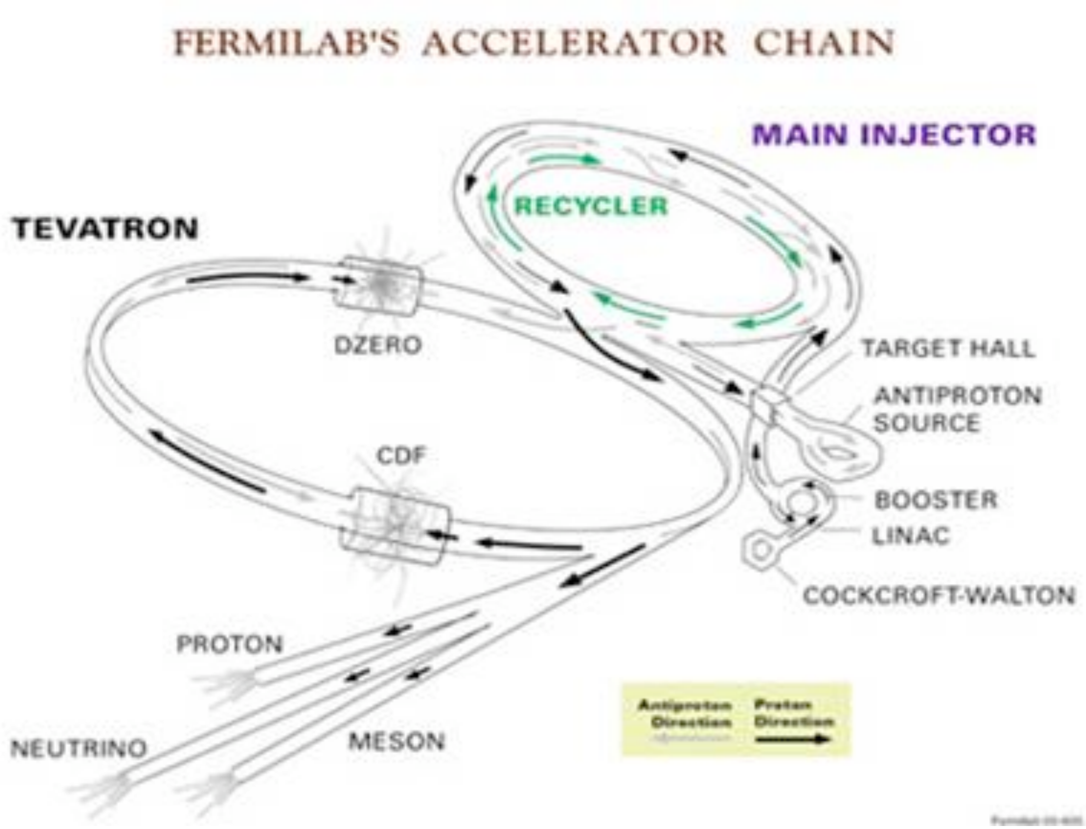
Conclusion : ALEPH has a 3σ observation of an excess, not confirmed by the other experiments…

… but the combination is consistent (although not significant) with the production of a 115.6 GeV/c^2 Higgs boson

Searches at the TeVatron

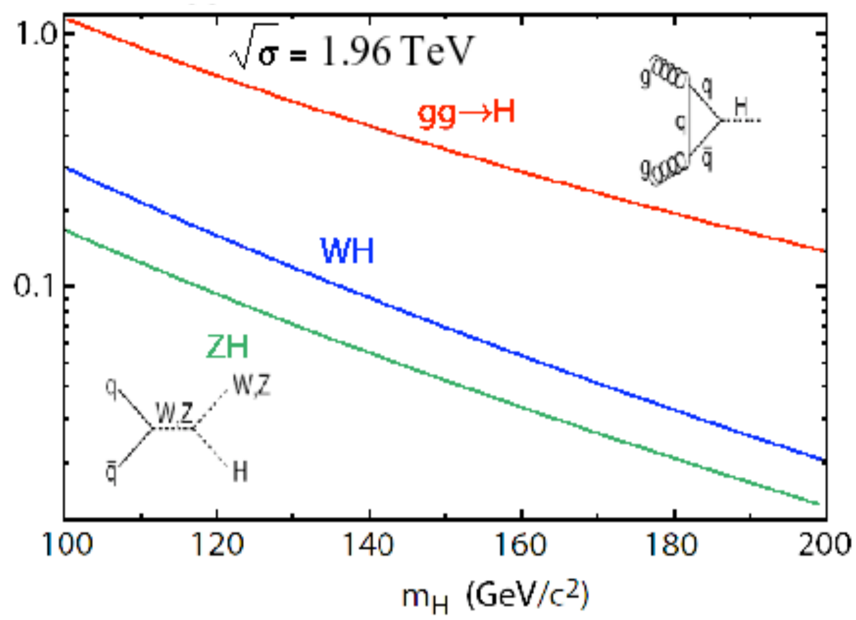
Searches at Present

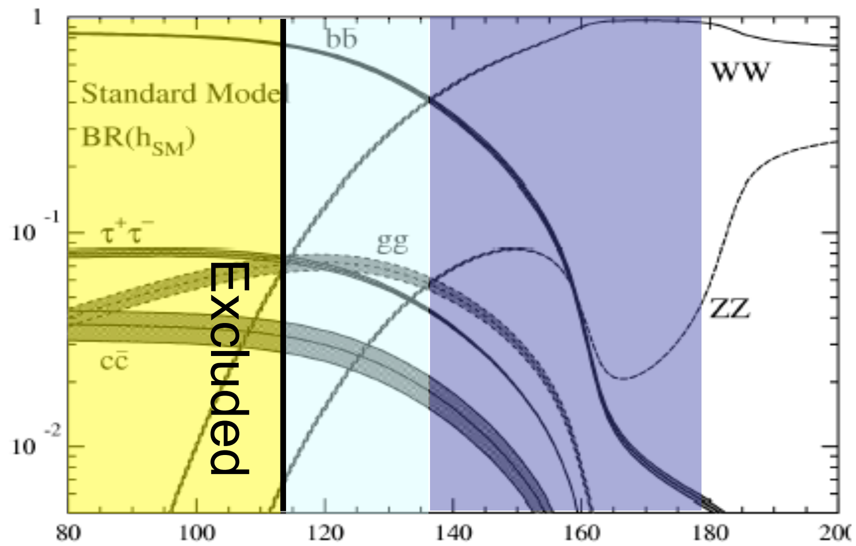
The TeVatron Machine



2 TeV centre-of-mass energy of proton/anti-proton collisions

Higgs Boson Phenomenology at the TeVatron





Low mass Higgs searches

High mass Higgs searches

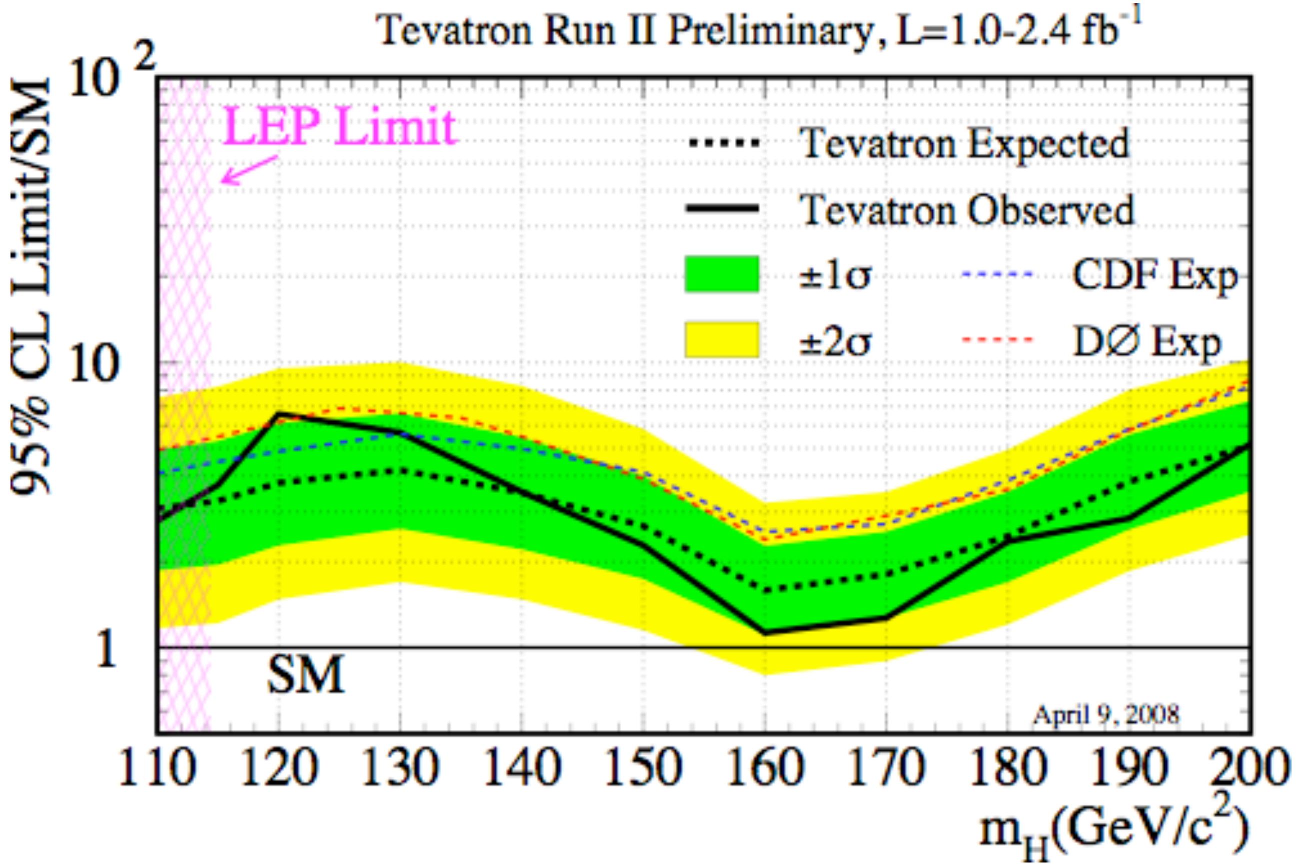
From associated production

$$\begin{cases} WH \rightarrow l\nu b\bar{b} \\ ZH \rightarrow llb\bar{b} \\ ZH \rightarrow \nu\nu b\bar{b} \end{cases}$$

$$H \rightarrow WW$$

From gluon fusion

Present Experimental Limit at the TeVatron



160-170 GeV Higgs bosons essentially ruled out…

Can the standard model be valid up to M_{Pl}?

Searches at the LHC

Near future searches, just a few significant examples...

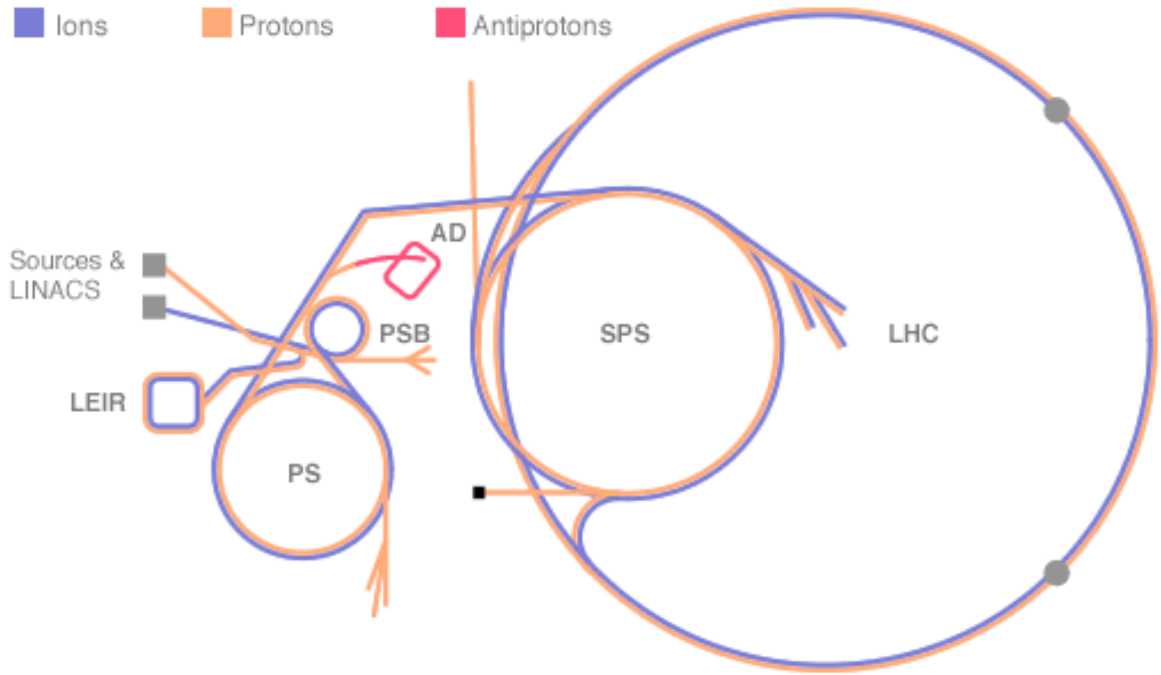
The LHC

- Housed in the LEP tunnel (27 km)

- Centre-of-mass energy for pp of 14 TeV i.e. Dipolar field of 8.33 T (1232 Dipoles)

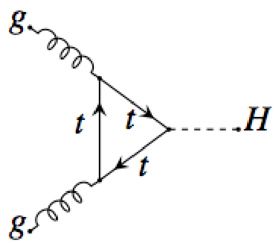
- Expected luminosity of 1033 to 1034, using 2800 bunches i.e. 25 ns crossing intervals (40 MHz incoming bandwidth)

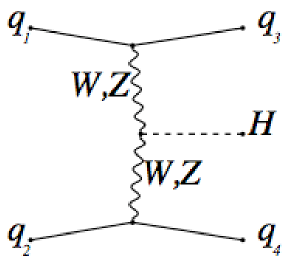
- Triggering system is <u>crucial</u>



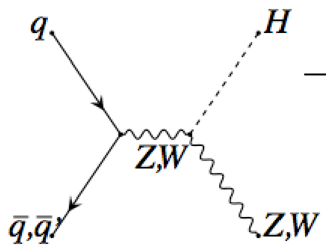
Production Processes

Gluon Fusion

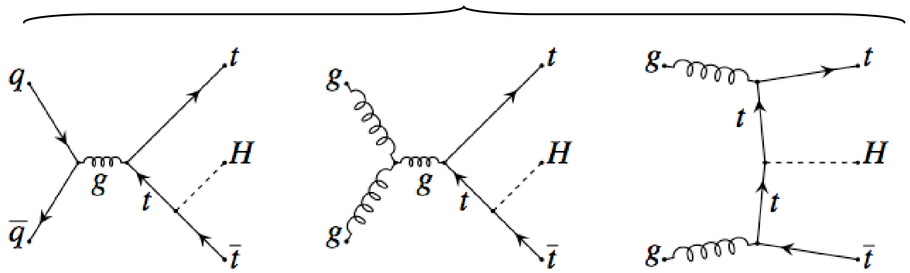


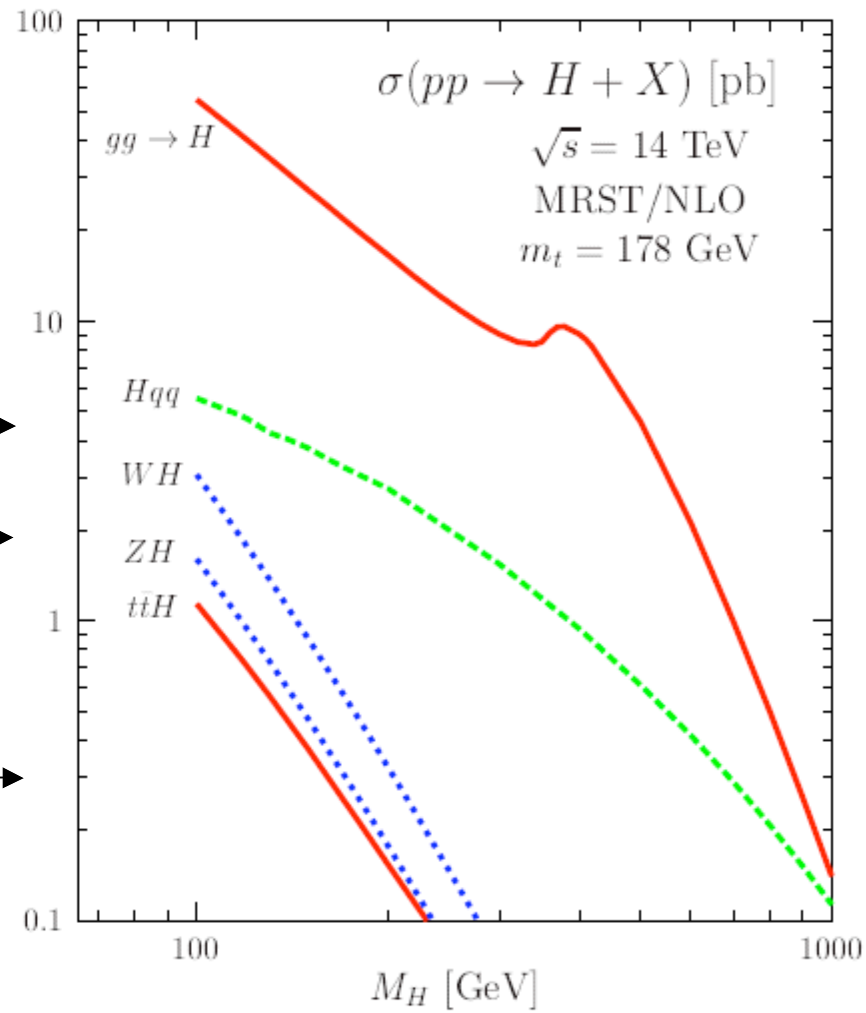


Vector Boson Fusion

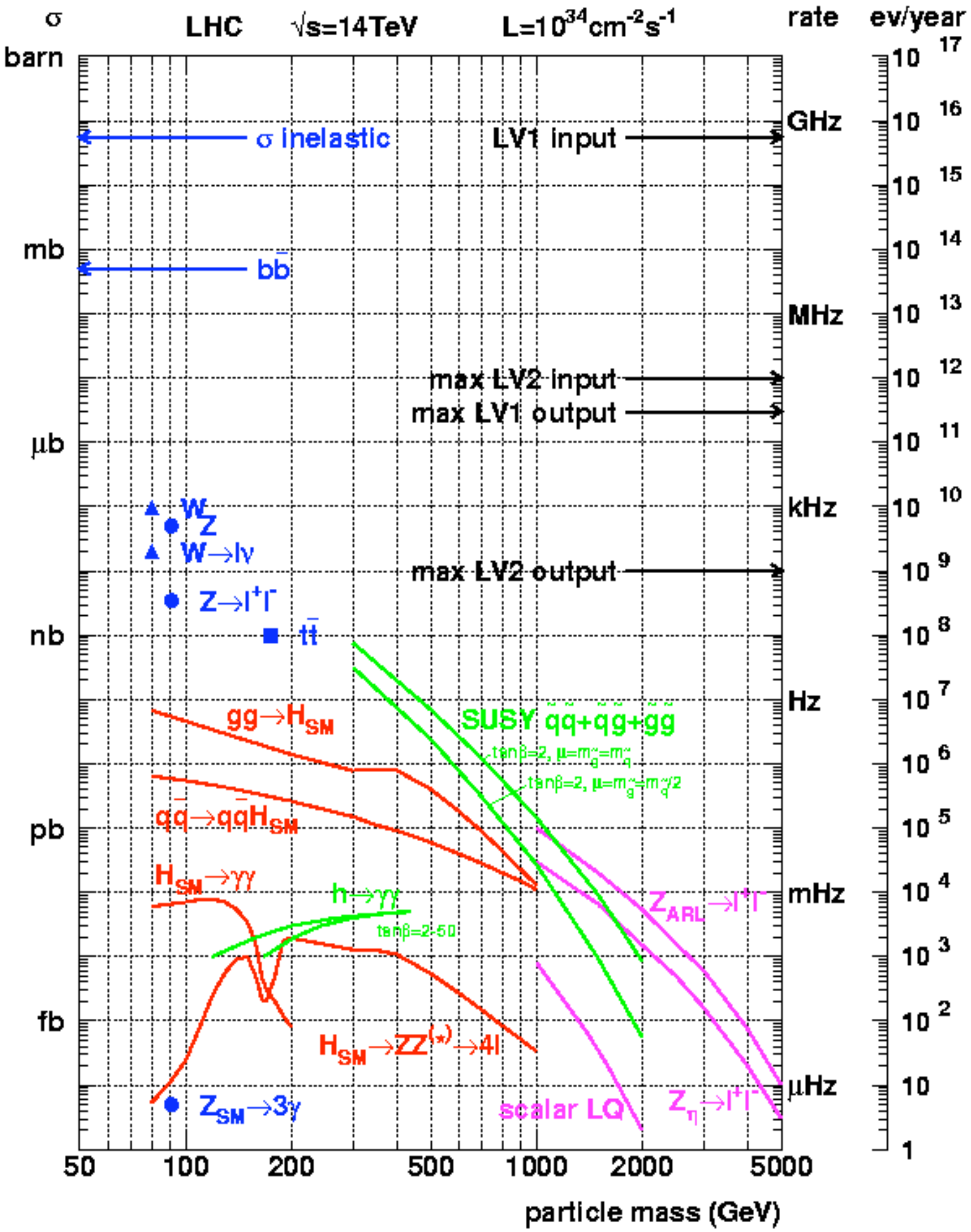


Associated Production





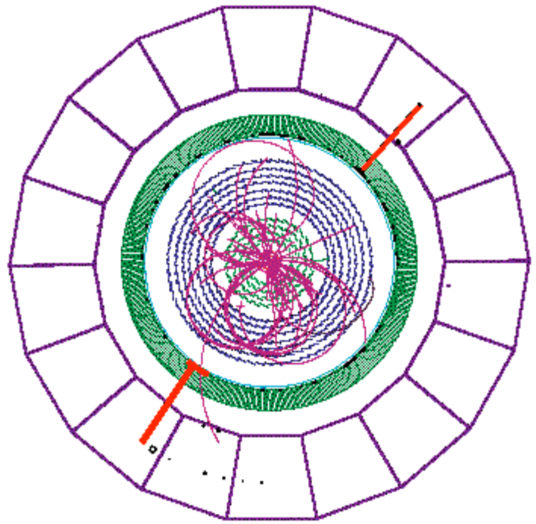
Background Processes



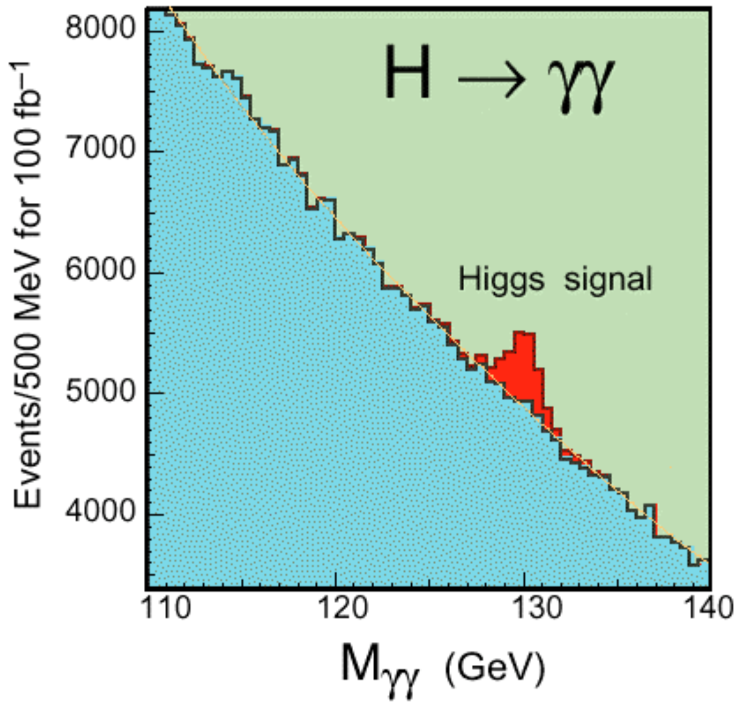
- At the LHC cross sections are huge

- Finding the Higgs boson is like searching for a needle haystack!

Low Mass Channels : $H \rightarrow \gamma\gamma$

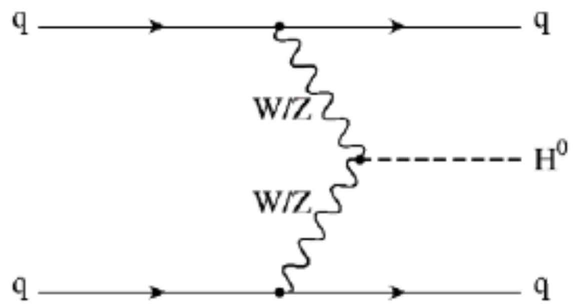


- Topology: two high P_t γ
- Background: irreducible pp→ $\gamma\gamma$ +x
  reducible pp→γj, (jj), …
- Exp. issues (mainly for ECAL):
  1.- γ, jet separation
  2.- mass resolution (~1%)
- Precise background estimate from sidebands

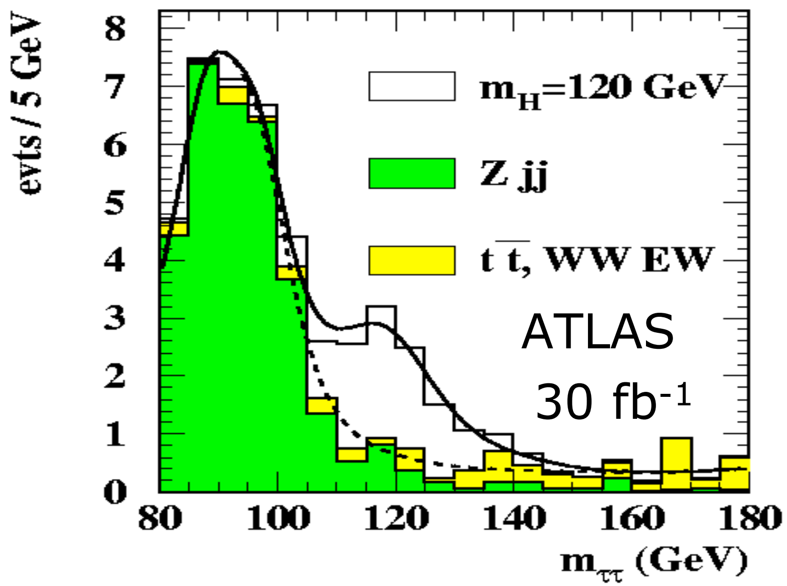


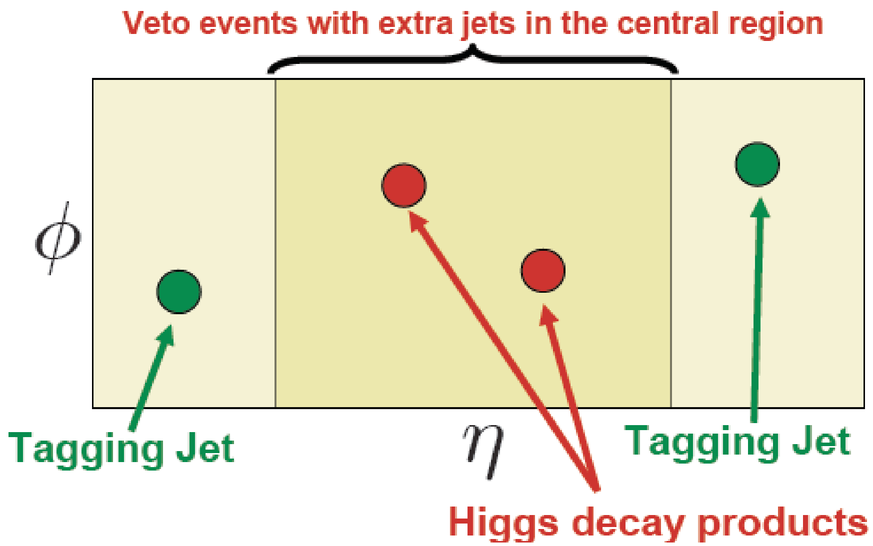
Low Mass Channels : VBF H→ττ

- Topology: 2 high p_t isolated leptons, missing ET
- Irreducible BG: VBF Zjj
- Reducible BG: Zjj and tt



Problem color singlet overwhelmed by color octet…

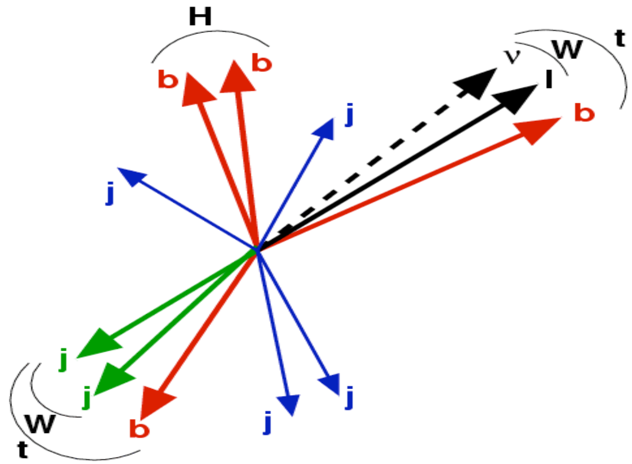


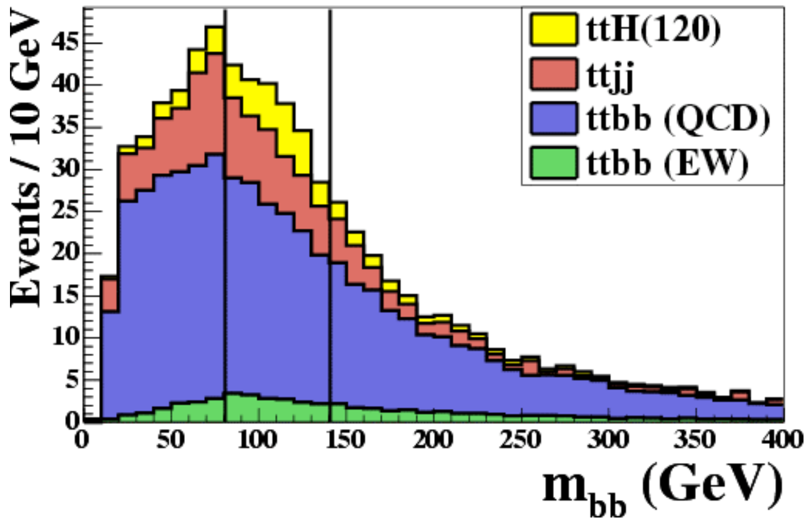


Very nice but difficult channel (systematics)

Low Mass Channels :
Very difficult associated tt production H→bb

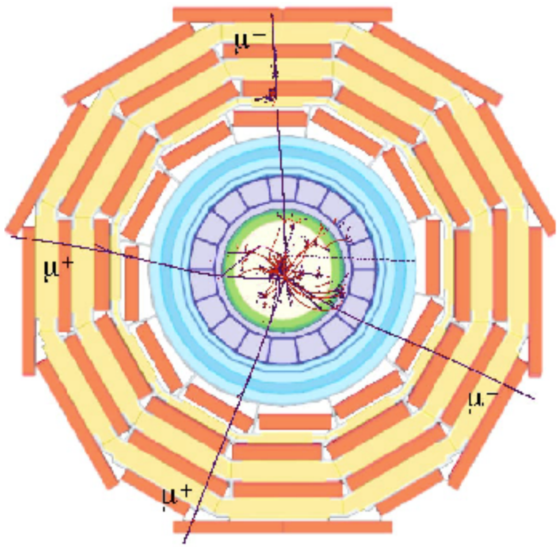
- Topology: 1 lepton, missing energy
  6 jets of which 4 b-tagged
- Reducible BG: tt+jets, W+jets → b-tagging
- Irreducible BG: ttbb → reconstruct mass peak



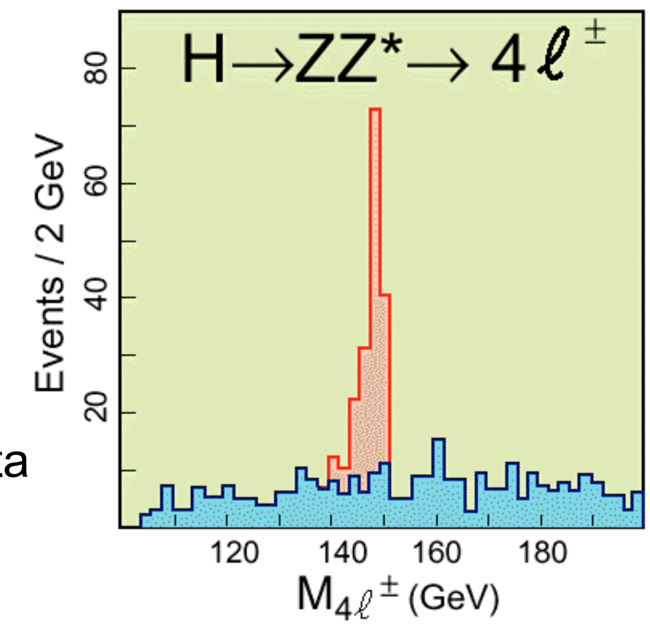


- Exp. issue: full reconstruction of ttH final state
- Mass resolution ~ 15% (50% correct bb pairs)
- <u>Very</u> difficult background estimate from data with exp. uncertainty ~ O(10%)
- Only channel to see H→bb

Intermediate and High Mass Channel : H→ZZ



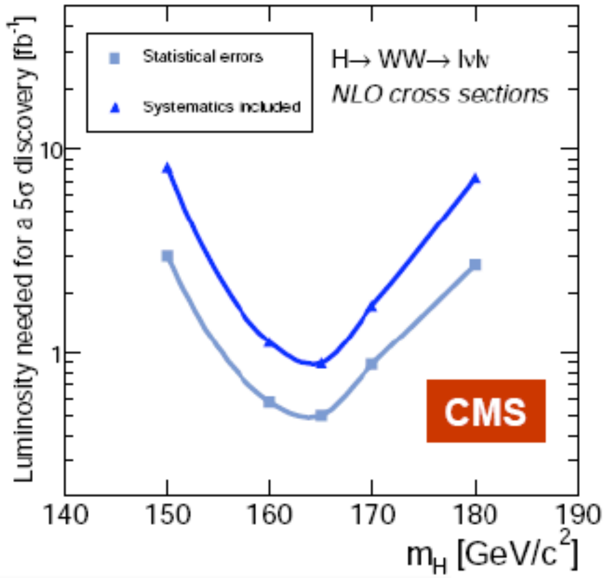
- Topology: 4 high p_t isolated leptons
  1(2) dilepton mass ~ M_Z
- Irreducible BG: ZZ → mass reconstruction
- Reducible BG: tt, Zbb → 4 leptons
  → rejection via lepton isolation and b-veto



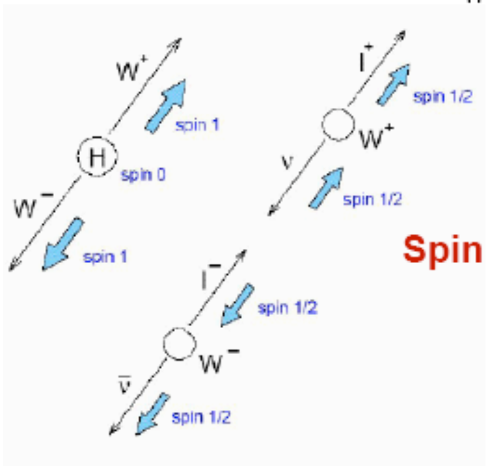
- good mass resolution σ_M: <~1%
- small and flat background → easily estimated from data

Intermediate Mass Channel : $H \rightarrow WW$

- Topology : 2 high p_t isolated leptons, missing ET
- Irreducible BG: WW → use spin correlations
- Reducible BG: tt → dileptons use jet veto

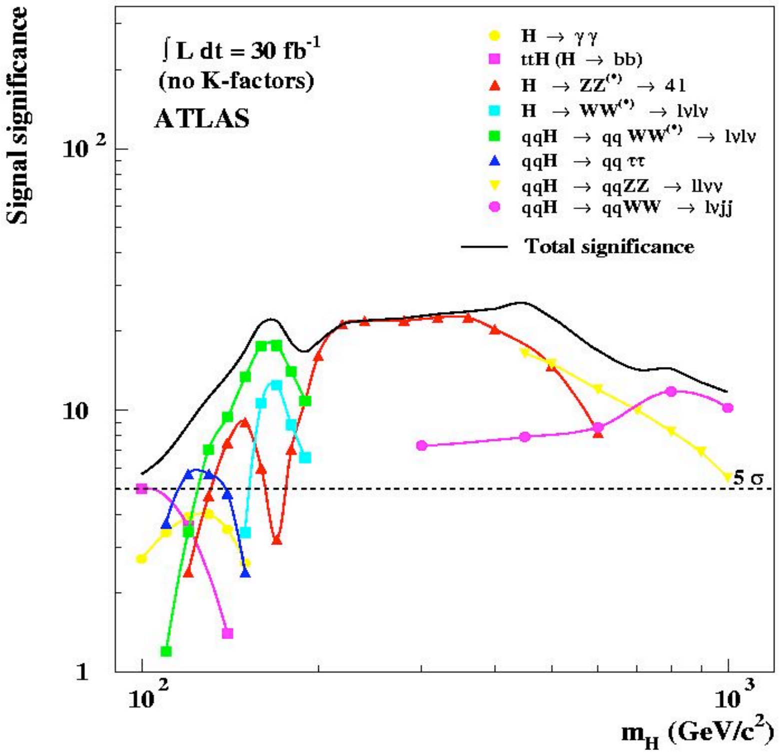


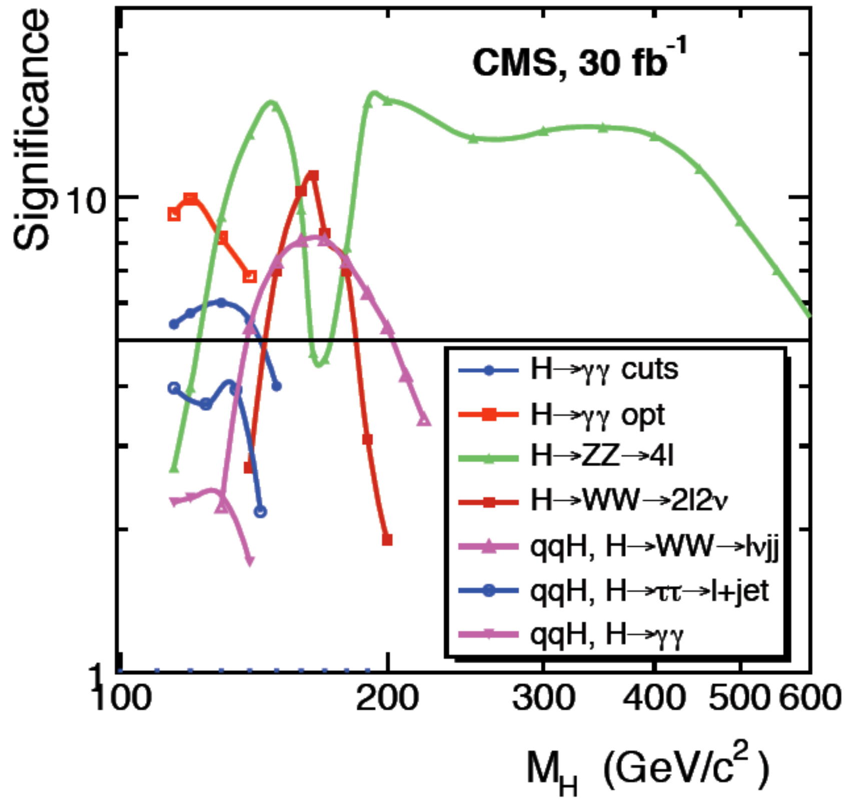
Fast discovery channel
(Higgs mass between 160-170 GeV... Sigh...)



Spin correlations

Sensitivity to the Standard Model Higgs boson at LHC





- ATLAS sensitivity soon completely revised
- The full allowed mass spectrum is covered at LHC
- Further supporting evidences will come from relative couplings of the Higgs and at High mass from the spin measurement (4 leptons)

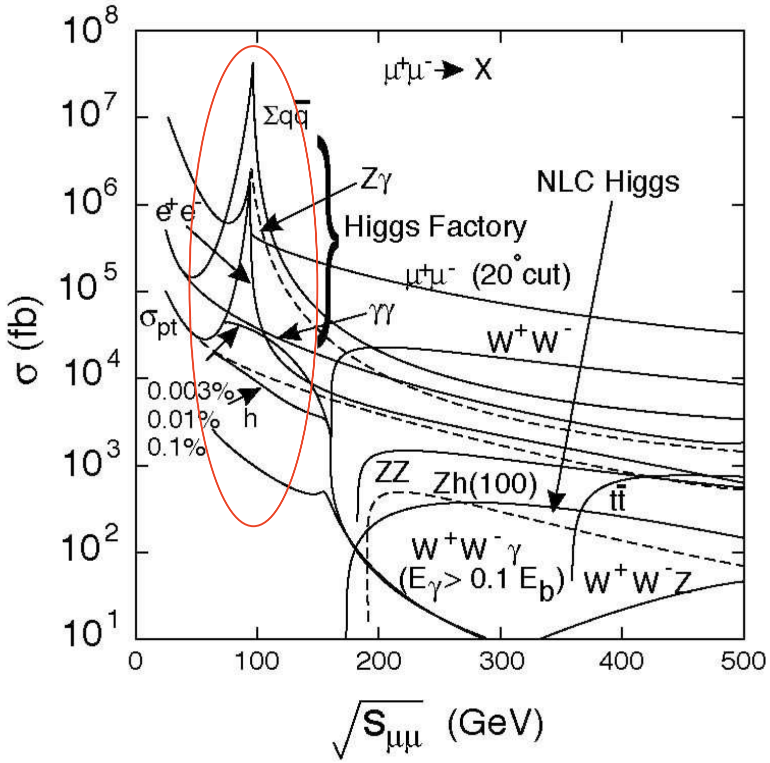
Searches at Future Colliders

Far future searches

Searches at Linear Collider : see Zhiqing Zhang's talk

Idea for future generations : Muon collider

Far stretched… ...but it could be a Higgs Factory



Conclusions

The Higgs mechanism is a key element in the standard model

Partly Corroborated

Missing key element : The Higgs boson

Highly desired particle, we can do without it but not for free

In all likelihood, either the Higgs boson exists or something new should appear at the TeV scale (unitarity - strong dynamic)

If it exists it also introduces a fine tuning problem, which strongly motivates new theories beyond the SM such as SUSY

EW precision fits favour a low mass Higgs boson (so does the MSSM)

TeVatron starts to cover the region where the Higgs mass implies that the SM can be valid up to M_{Pl}

Many apologies for the enormous number of uncovered topics in these lectures

Conclusions

The LHC will very likely shed light on some of these questions

Many apologies for the enormous number of uncovered topics in these lectures