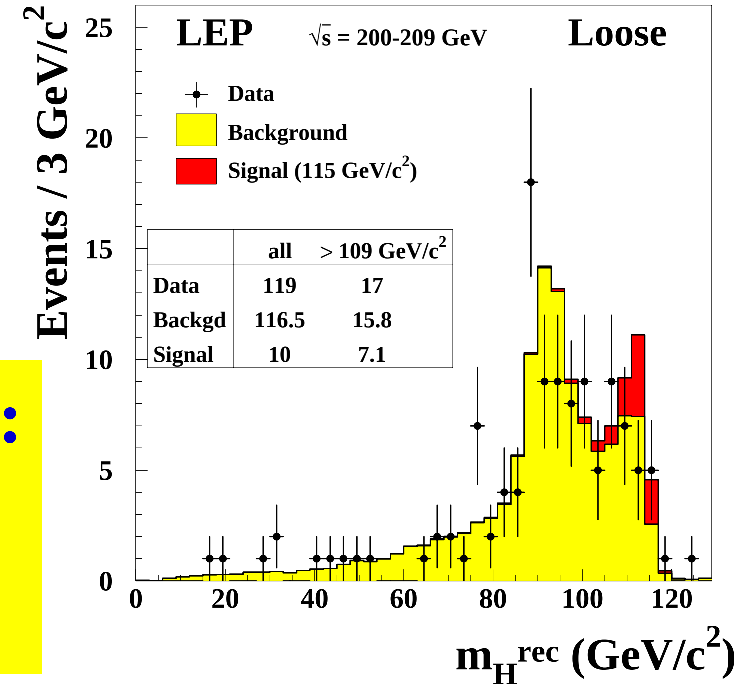
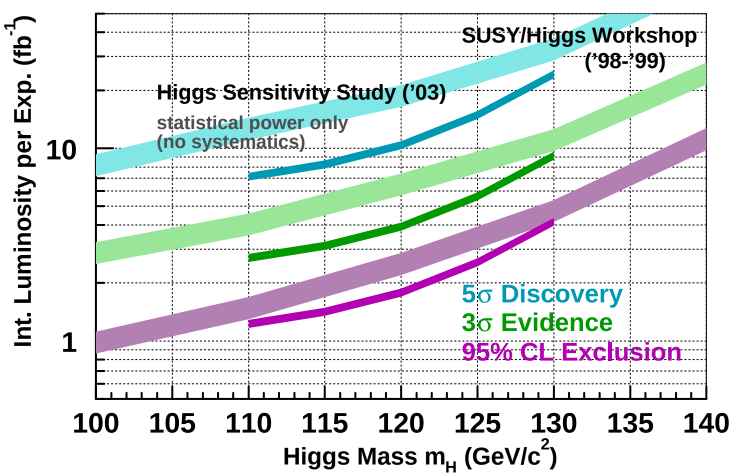
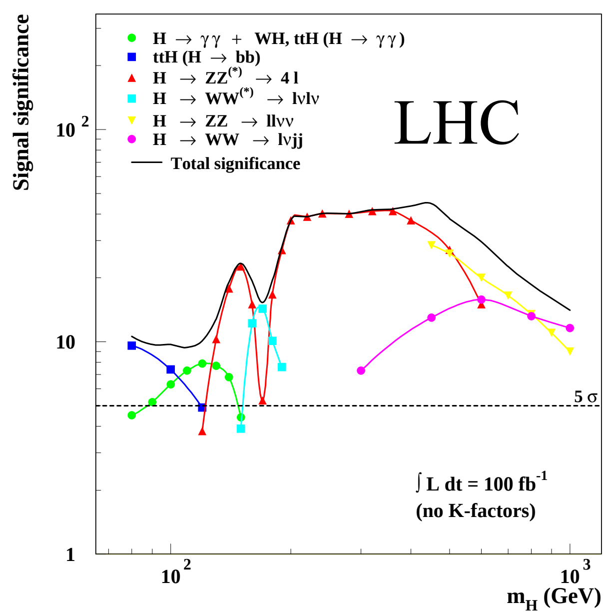




# Electroweak Symmetry Breaking: Experimental Status Report

Peter Ratoff
Lancaster University

Tevatron

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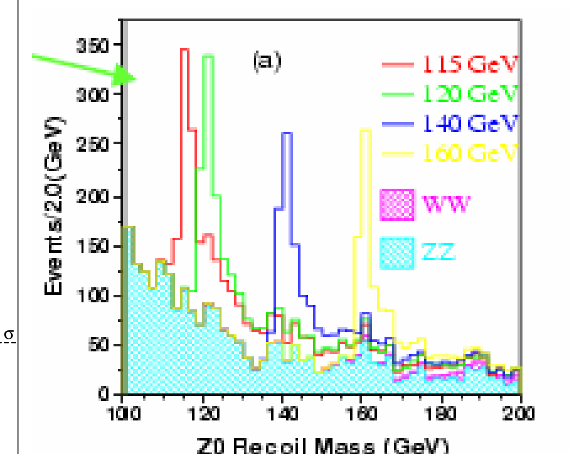


# Outline

- Introduction
- Precise EW limits (very brief - see Bob Clare's talk)
- LEP Higgs Search – the (recent) past
- Tevatron Higgs Potential – the 'present'
- LHC Higgs Prospects – the (near) future
- $e^+e^-$ Linear Collider Higgs Prospects – the (far) future
- Summary/Conclusions

~ almost no theory – see Sally Dawson's talk

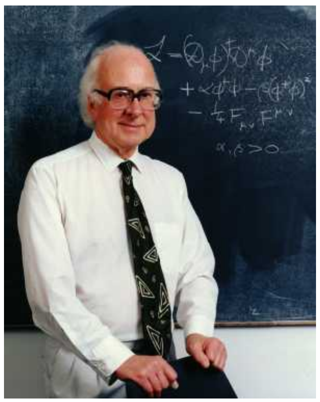
# Electroweak Symmetry Breaking – The Higgs Mechanism

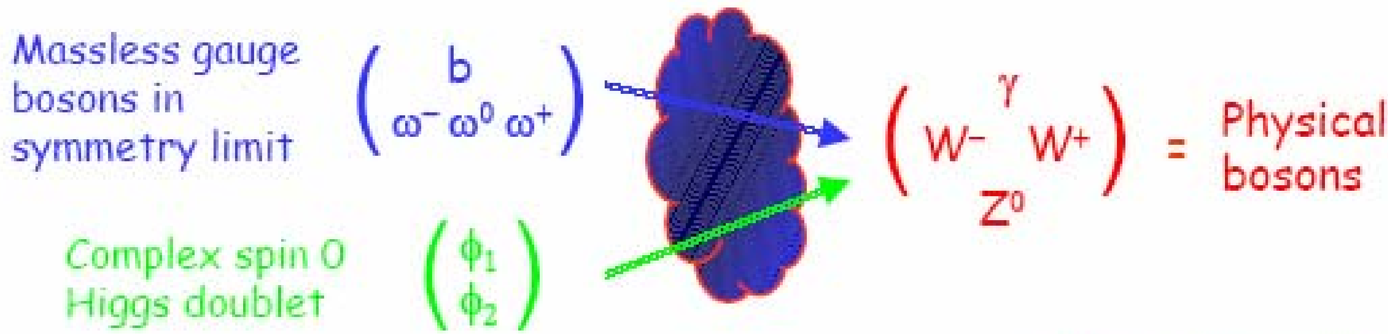
The observed Weak force is ~ 1 fm, so the physical $W^{\pm}$ and $Z^0$ bosons must be massive.

$M_W = 80.450 \pm 0.034$ GeV , $M_Z = 91.1875 \pm 0.0021$ GeV.

Observed W/Z cannot be Yang Mills gauge bosons: EW sym is broken.

In the Standard Model, we invoke the spontaneous symmetry breaking of the unified EW force:






(Thanks: Paul Grannis!)

3 of Higgs degrees of freedom go to provide the missing longitudinal polarization state needed by massive vector bosons.

Before symmetry breaking: 4x2 gauge boson d.o.f. and 4 Higgs d.o.f.

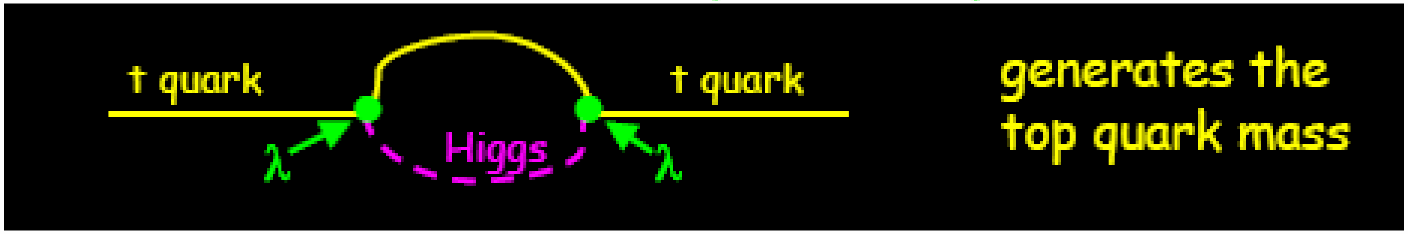
After, 3x3 for $W^{\pm}/Z$, 2 for $\gamma$ and 1 Higgs d.o.f. left over

# The Higgs Boson

In the Standard Model, the 4th Higgs field results in the HIGGS BOSON. All the parameters of the EW interaction are fixed by experiment, except for the Higgs boson mass.

Higgs gives mass to W and Z - and quarks & leptons too

e.g.




The more massive the quark, the larger its Yukawa coupling λ.

Many observables of the Z and W bosons are dependent upon the mass of the Higgs boson.

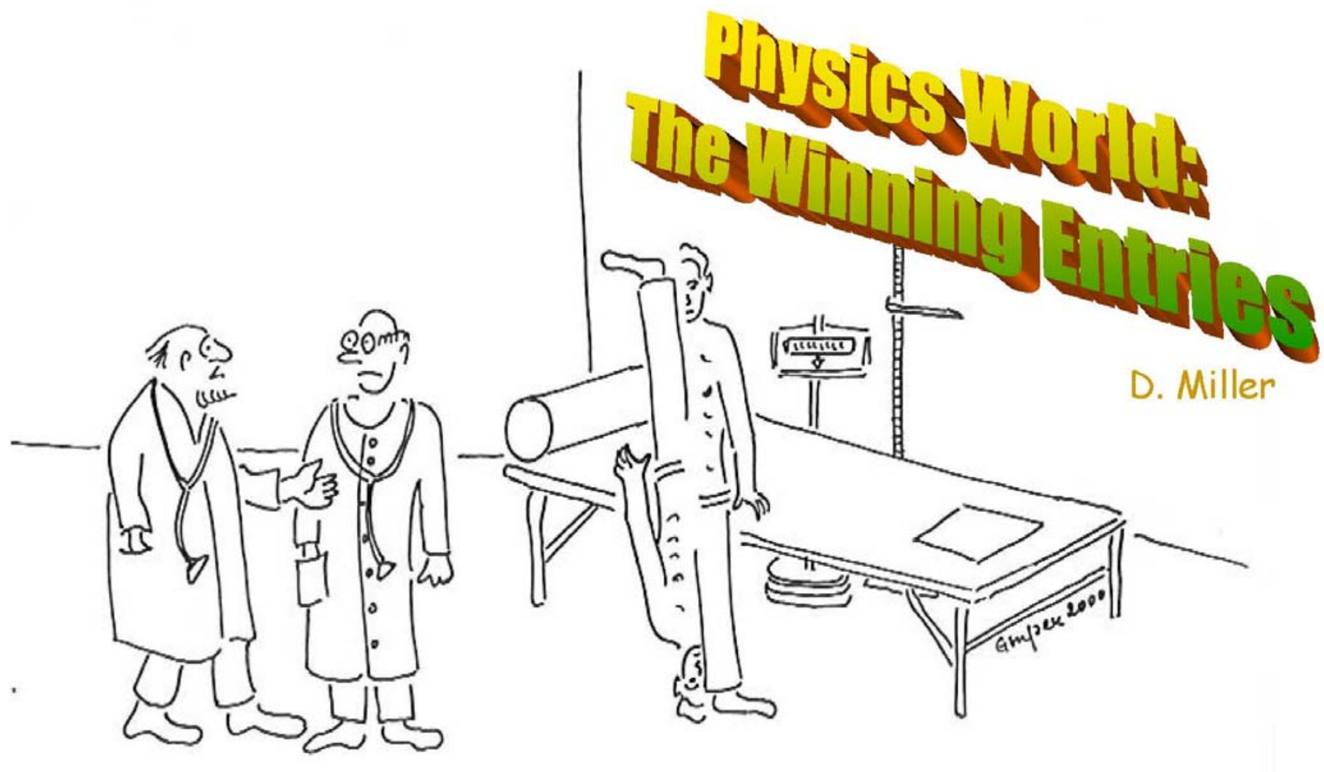
**In the context of the SM, the many precision measurements of the properties of Z, W, top quark indicate:**

$$114 < M_H < \sim 200 \text{ GeV}$$

Of course, Nature may choose some other way than SM to break Electroweak symmetry! (see Sally Dawson's talk)

# The Waldergrave¶ Challenge

… to UK particle physicists: "Explain the Higgs boson to the general public"

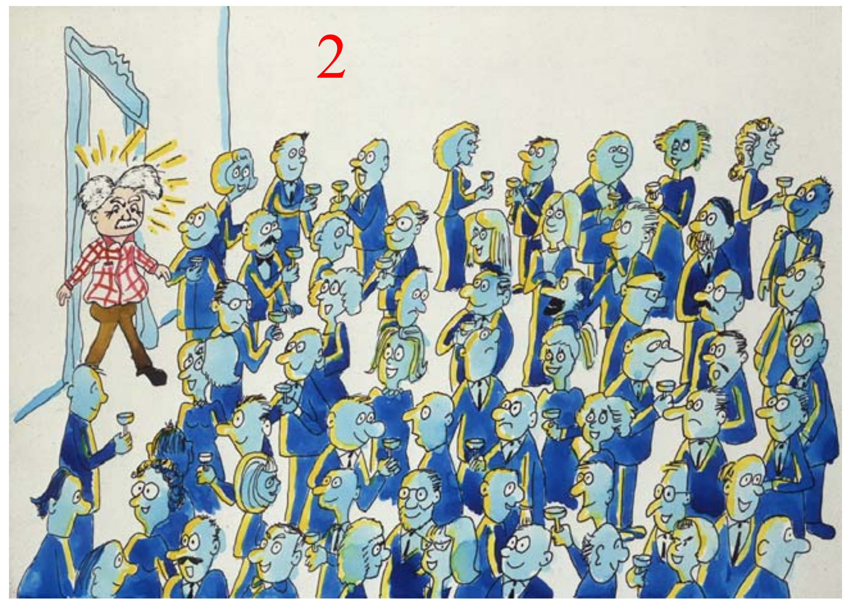


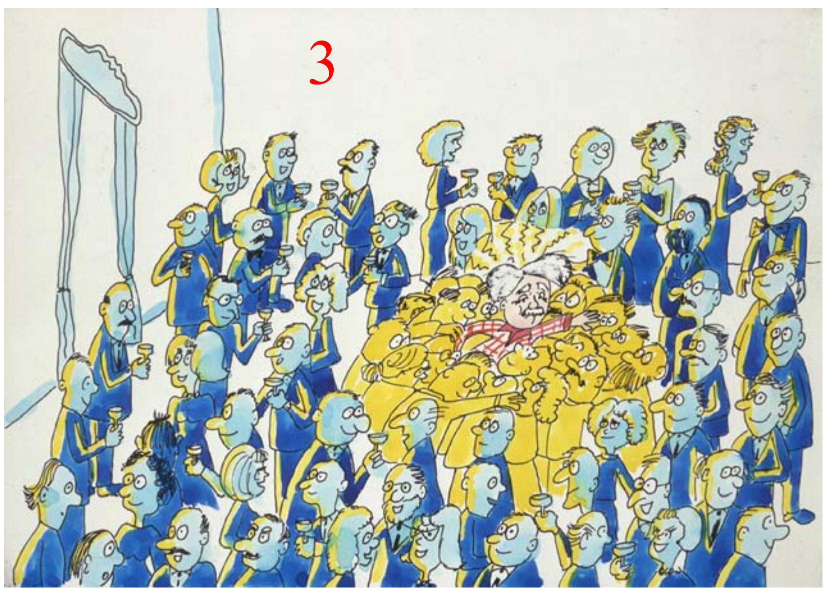

A severe case of symmetry breaking

¶ William Waldergrave, UK Science Minister, late 1980's

# Higgs enters the broader culture …


Higgs field generates all masses …




$m_f$ = resistance to movement

$\nu$ = density of the crowd (“Vev”)

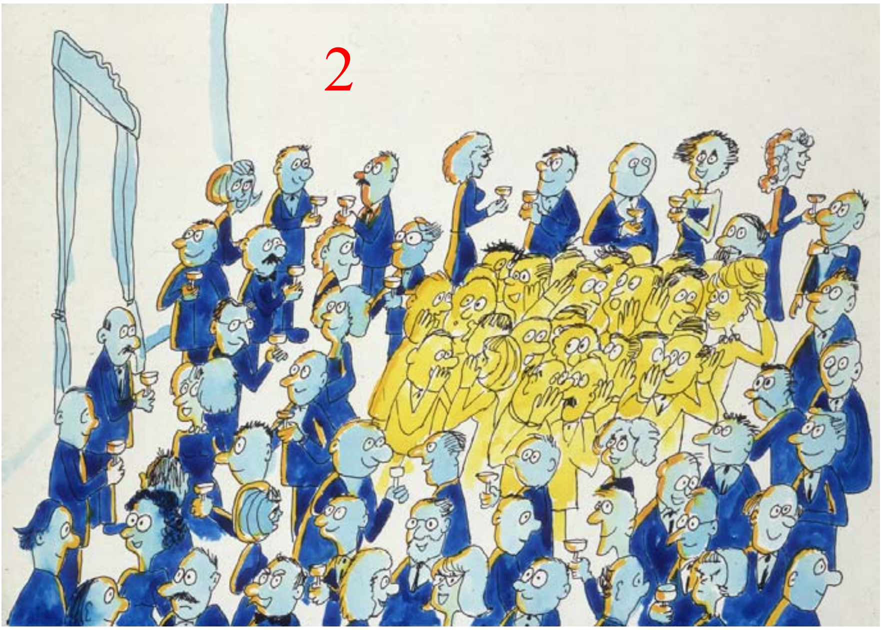
$m_f = g_{Hff} \, . \, \nu$

# …with a prize winning explanation!

Higgs generates its own mass …
(but its value is unknown)

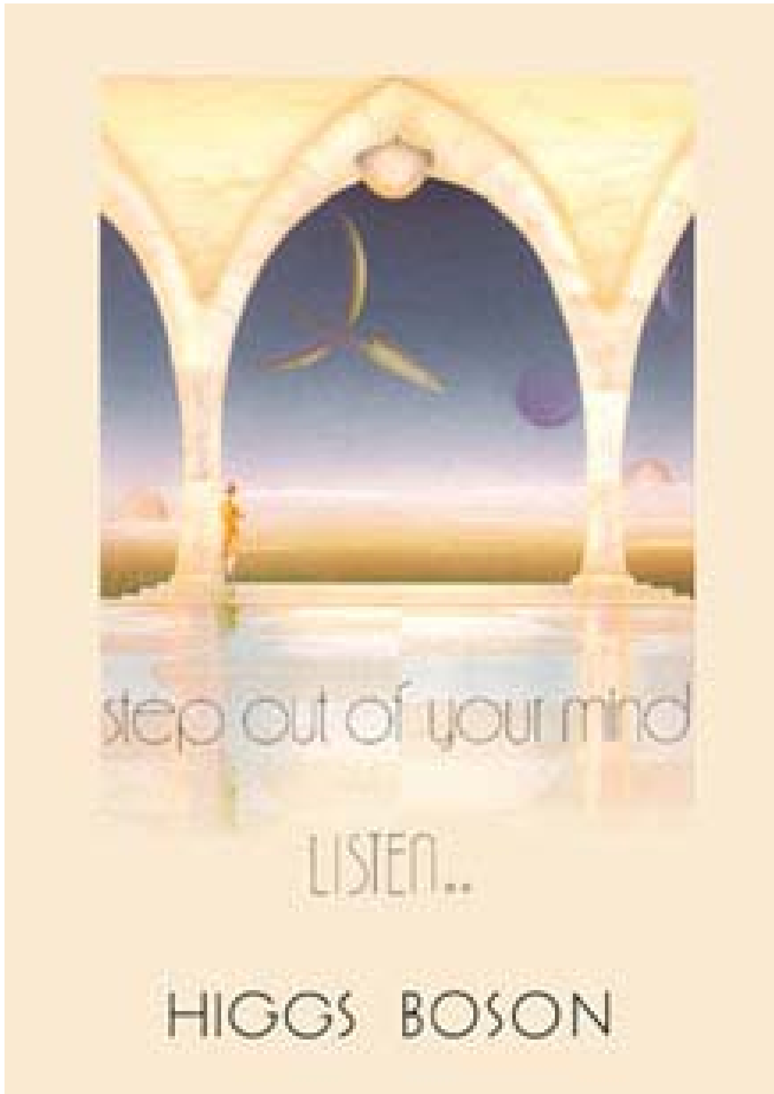
$$M_H^2 = 2\,\lambda v^2$$

$$V = \mu^2\,|\Phi^2| + \lambda\,(|\Phi^2|)^2 \quad (\mu<0)$$

# … and the cultural connection broadens!

… into contemporary Music

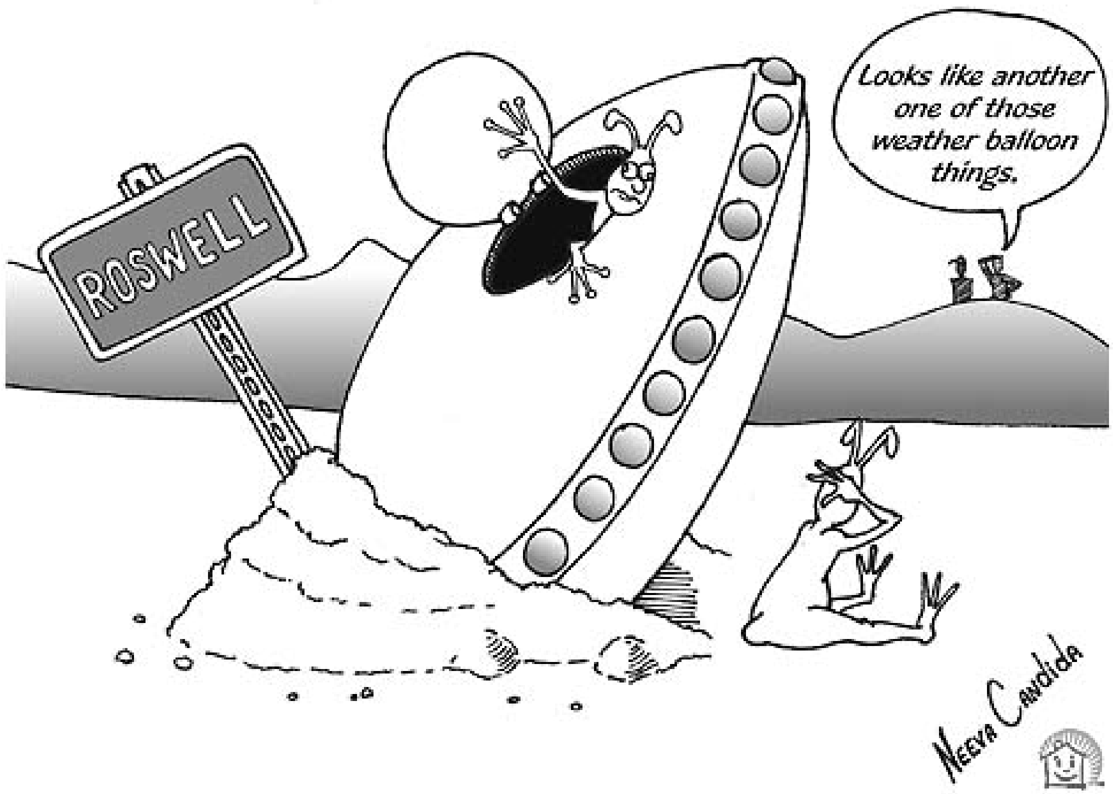



Higgs Boson -
28 year old British Jazz Fusion Piano/Keyboard artist

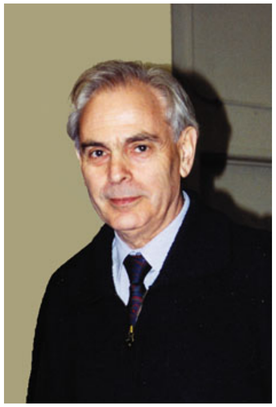
www.higgsboson.fsnet.co.uk

# A brief history of Higgs searches

Many reported ‘sightings’, but none confirmed … !




1981-2001 ...Two decades of increasingly tighter limits, spurious signals, moments of great excitement, but many disappointments ...



# L.Okun's Summary Talk: LP'81

Lepton Photon Symposium, Bonn, 1981

…. described *scalar particles* as the #1 problem in particle physics!

"Scalars are at the epicentre of particle physics. The theoretical seaquake, the eruption and tumbling of numerous theoretical models, heralds the birth of a new physical continent."

"Painstaking search for light scalars should be considered as the highest priority for the existing machines such as *CESR*, *PETRA*, *PEP* and the CERN *SPS Collider*, and even more for the next generation of accelerators, such as *LEP, Tevatron, UNK, and HERA.* Especially promising is the project of a very high energy *electron-positron linear collider*. The future of theoretical physics depends on the **energy** and **luminosity** of these machines."

n.b. LHC/SSC not even on the horizon!

# Technipion search at PETRA (1981)

First (?) search for new scalar particles ...

Reported at LP'81 (Bonn)

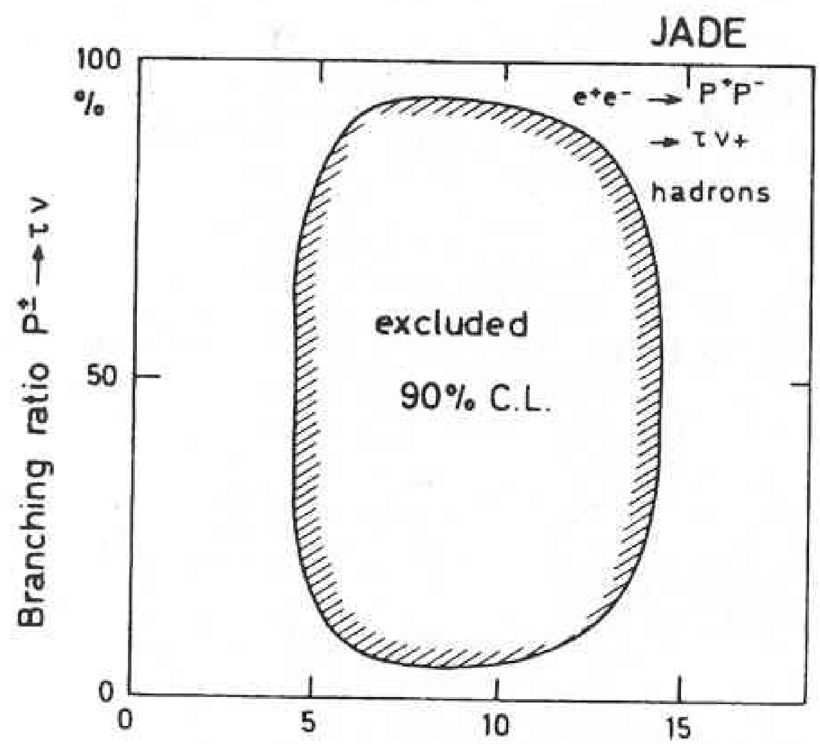
***Dynamical symmetry breaking* by bound states of new types of quarks and leptons with super-strong interactions called *technicolour***

**Quartet of *scalar* colour singlet Goldstone bosons (technipions) predicted in a minimally extended technicolour scheme**
**=> technipion masses ~ 10-20 GeV ?**

**Search for e+ e- → P+ P- → τ + ν + hadrons**

**=> 2 acoplanar jets, one consistent with τ decay**

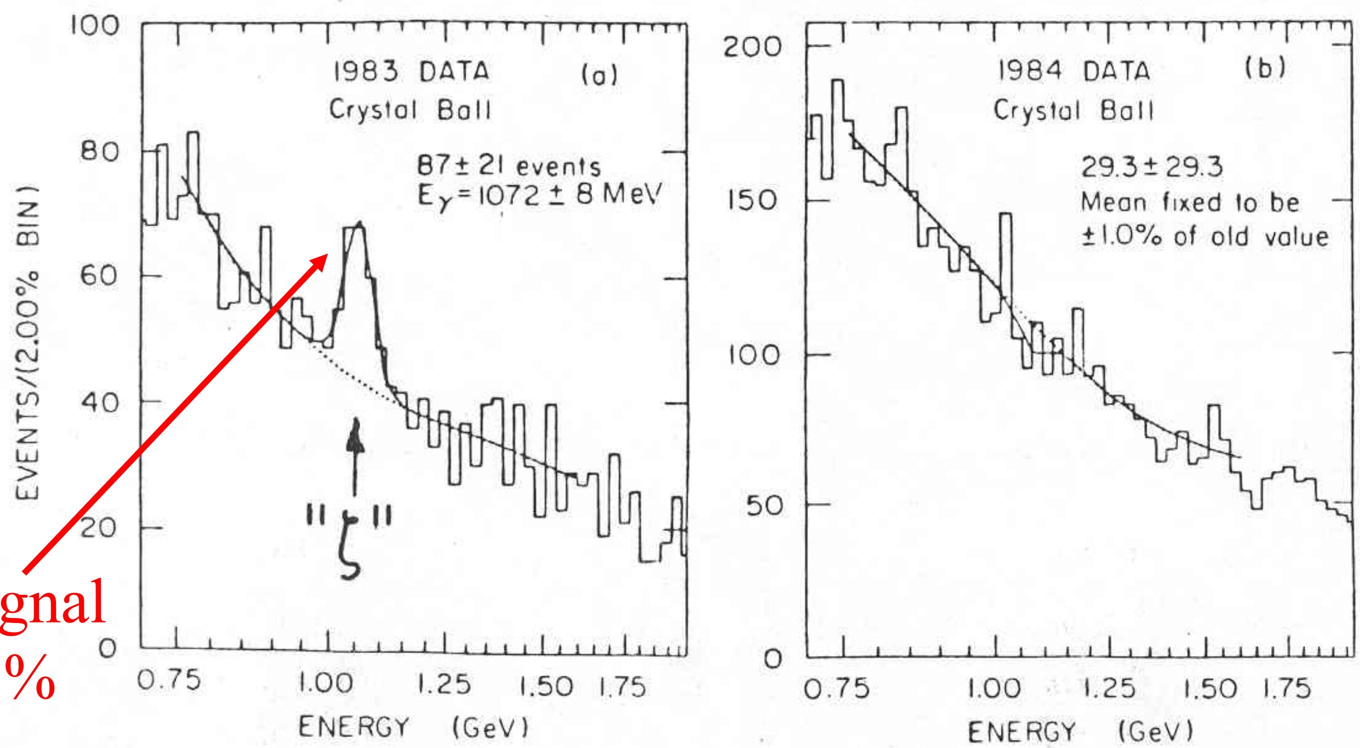
**n.b. this search also sensitive to charged Higgs bosons in SUSY models; they have similar properties to the charged technipions**



# Crystal Ball's Zeta(8.3)

e+e- $\rightarrow \Upsilon(1S) \rightarrow \gamma + X$ DORIS(DESY)

LP'85




4.1 σ signal
BR~0.5%

Fig. 15. Crystal Ball evidence for (a) and against (b) the $\varsigma(8.3\ GeV/c^2)$ state.

Wilczek mechanism (Heavy Quarkonium radiative decay): $Q\overline{Q} \rightarrow \gamma + H$

BR($J/\psi \rightarrow \gamma$ + H) ~ 6 x $10^{-5}$ BR($\Upsilon \rightarrow \gamma$ + H) ~ 2.5 x $10^{-4}$

n.b. CESR(CUSB) previously set 90% CL limit of ~ 3 x $10^{-3}$ (LP'83)

NEW YORK TIMES



# Physicists Discover Mystery Particle

By WALTER SULLIVAN

A new subatomic particle whose properties apparently do not fit into any current theory has been discovered by an international team of 78 physicists at DESY, a research center near Hamburg, West Germany. The group has named the particle zeta.

Dr. Elliott Bloom of the Stanford Linear Accelerator in Palo Alto, Calif., co-leader of the group reporting the zeta discovery, said in a telephone interview yesterday that the theorists "are puzzled," and added, "We really don't know what this beast is."

As described yesterday to a conference at Stanford, the zeta particle has some, but not all, of the properties postulated for an important particle, called the Higgs particle, whose existence has yet to be confirmed. Confirmation of that particle's existence would be a major landmark in physics and would explain certain asymmetries in the basic properties of matter and the forces controlling its behavior.

Indeed, one Higgs particle may,have been detected in a different experiment at DESY, although that result remains ambiguous.

**Changes in Theory Necessary**

The existence of the Higgs particle was proposed some years ago by Peter Higgs of the University of Edinburgh, in part to explain why the particles transmitting some basic forces that operate on an atomic level are very massive while carriers of the electromagnetic force — light waves and other photons — are without mass.

Those with mass, it was proposed, acquire it from a field generated by Higgs particles. The zeta could be "a funny Higgs, a nonstandard Higgs," said Dr. Bloom, but in that case basic changes in the theory are necessary.

Some theorists believe that the ...

ther two or three quarks. Quarks are subatomic particles that always exist in pairs or triplets. They fall into six categories, the last and most massive, called the top quark, having been discovered last June at CERN, the European Laboratory for Particle Physics near Geneva.

**Stanford Developed Detector**

The zeta finding reported in California yesterday was made with a "crystal ball" detector developed at Stanford and flown to Germany in an Air Force transport for installation at DESY, which in German stands for German Electron-Synchrotron.

Electrons, which carry a negative electric charge, and positrons, their positively charged twins, are accelerated by the DESY synchrotron. They are then injected into DORIS, a small storage ring, to circle in opposite directions, or into the larger PETRA ring, which encircles the entire center.

Both facilities are used to observe the many exotic particles created when very high energy electrons and positrons collide head on. Late last year, the collision energy in PETRA was increased from 43.2 to 45 billion electron volts.

The energy released by such collisions can materialize into particularly massive particles, although the particles are so short-lived that they can usually be detected only in terms of their decay products.

Only one of the four detectors in PETRA, known as CELLO, detected the single occurrence of a particle, which some believe could be a Higgs. Its observation was described in a journal CERN Courier article entitled "CELLO Solo."

The crystal ball detector that was used is a sphere, 7 feet in diameter, formed of 672 sodium iodide crystals. When struck by high-energy particles, it gives off flashes of light indicating the energy of the impacting particle.

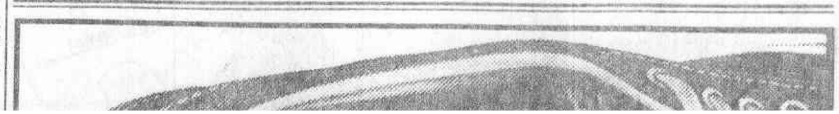
The sphere monitored the decay products of electron-positron collisions tuned to produce upsilon particles with masses of about 10 electron volts. The lightest of the three upsilons, with a mass of 9.46 electron volts (expressed, as customary, in terms of equivalent energy), appeared to give birth to a particle with a mass of 8.32 electron volts, which itself then disintegrated.

This might have been regarded, Dr. Bloom said, as production of the long-sought Higgs particle but for the fact that a more massive form of the Upsilon did not produce such daughters.

## Gulf Oil Slick 25 Miles Long

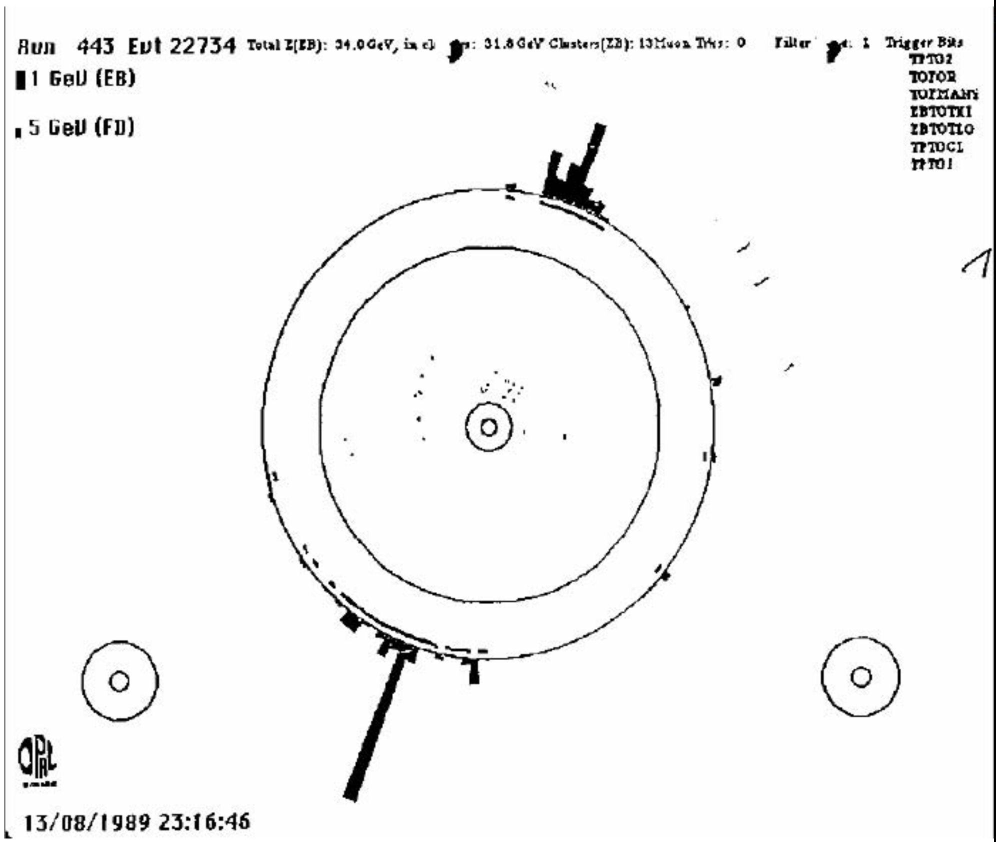
LAKE CHARLES, La., Aug. 1 (AP) — Workers pumped crude oil from a grounded British tanker into barges today and strung floating booms as far as 25 miles from the ship to contain an oil slick in the Gulf of Mexico. The oil was leaking from a 115-foot crack in the hull of the Alvenus, which ran aground Monday. Crews used huge water vacuums to suck the oil into a barge. The oil posed no threat to nearby wildlife refuges, a Coast Guard spokesman said.

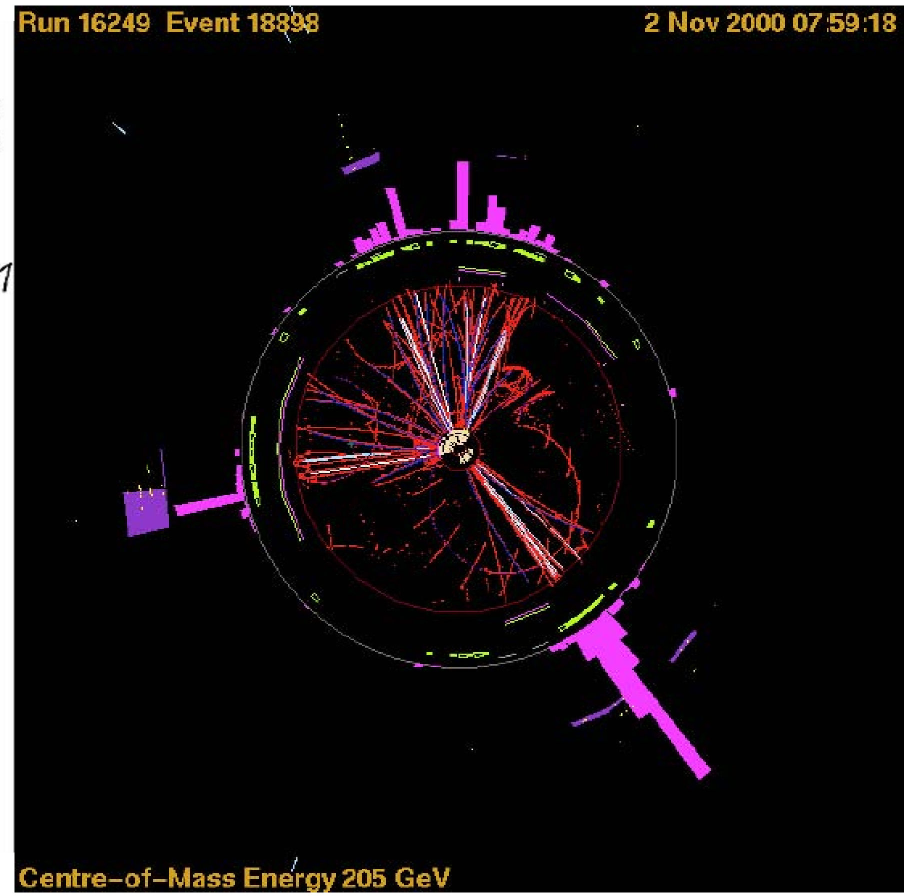




# 12 Year Higgs Search at LEP

## August 1989 – November 2000



# LEP SM Higgs Search Published (final paper!)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/2003-011
April 25, 2003

## Search for the Standard Model Higgs Boson at LEP

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP Working Group for Higgs Boson Searches[1]

Abstract

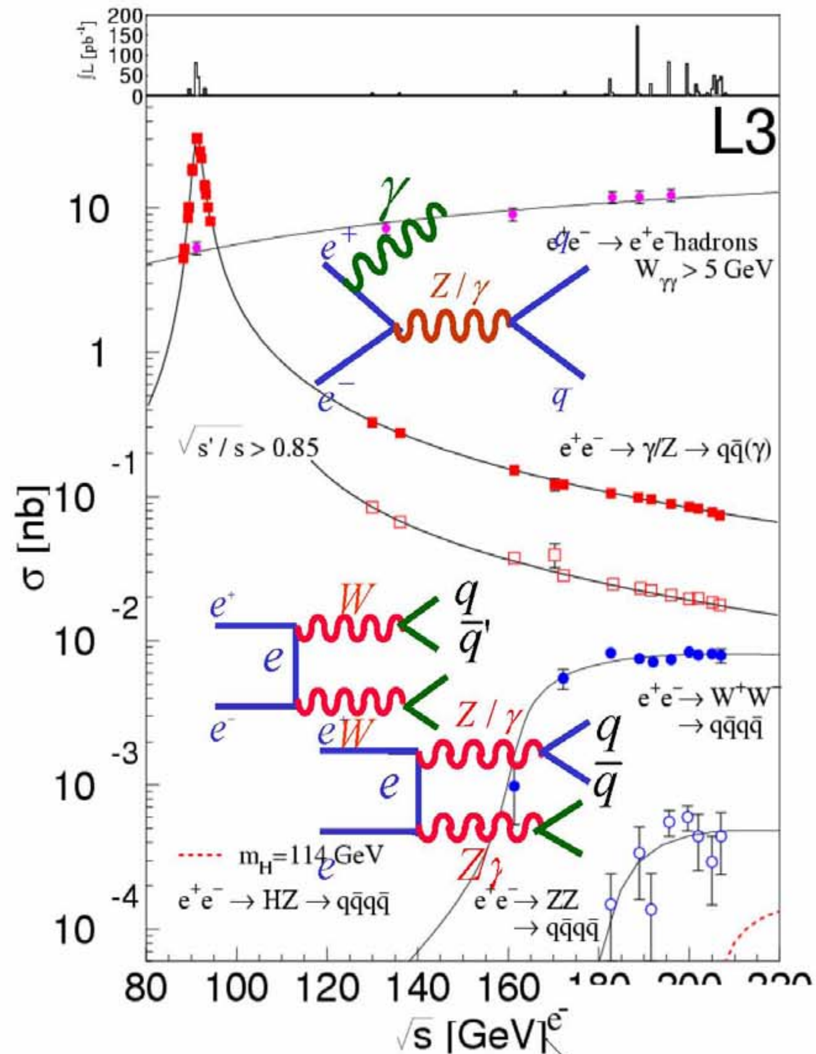
The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have collected a total of 2461 $\mathrm{pb}^{-1}$ of $e^+e^-$ collision data at centre-of-mass energies between 189 and 209 GeV. The data are used to search for the Standard Model Higgs boson. The search results of the four collaborations are combined and examined in a likelihood test for their consistency with two hypotheses: the background hypothesis and the signal plus background hypothesis. The corresponding confidences have been computed as functions of the hypothetical Higgs boson mass. A lower bound of 114.4 $\mathrm{GeV}/c^2$ is established, at the 95% confidence level, on the mass of the Standard Model Higgs boson. The LEP data are also used to set upper bounds on the HZZ coupling for various assumptions concerning the decay of the Higgs boson.

*Submitted to Physics Letters B*

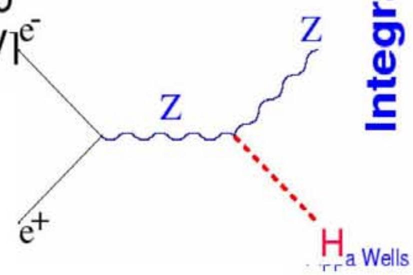
[1]The authors are listed in Refs. [9–13].

# Large Electron-Positron Collider

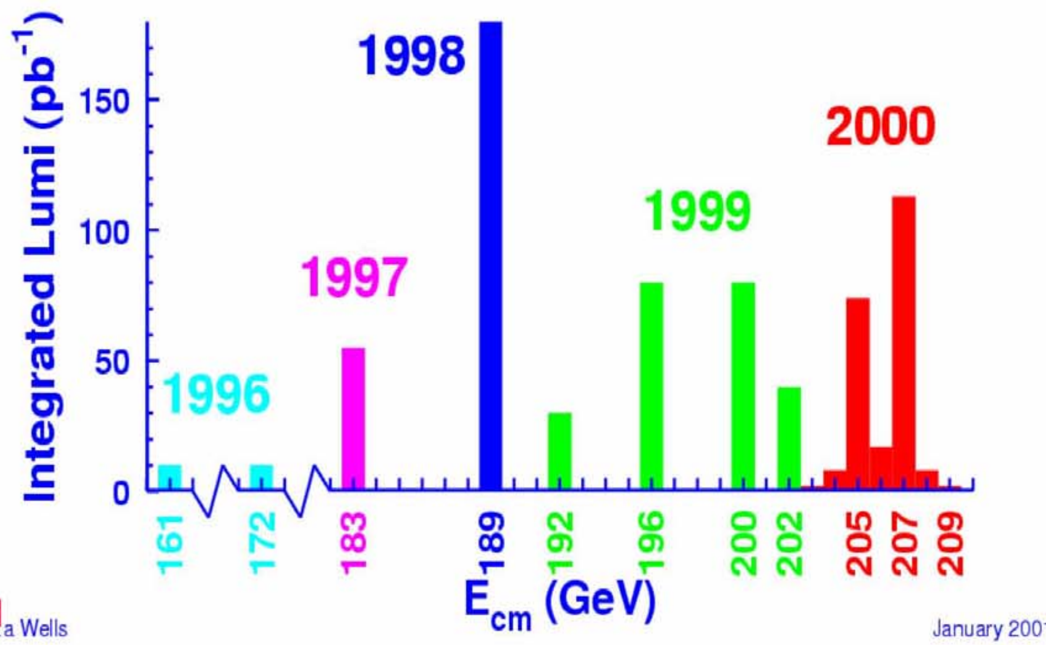
# LEP



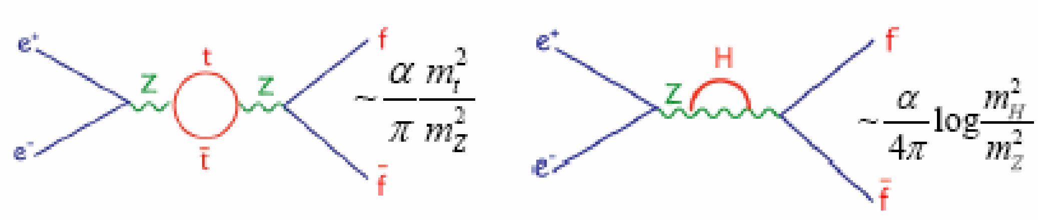

Total LEP I luminosity ~200 $pb^{-1}$/experiment
LEP II luminosity ~750 $pb^{-1}$/experiment




$$m_H^{max} = E_{CM} - m_Z$$



# The global EWWG fit



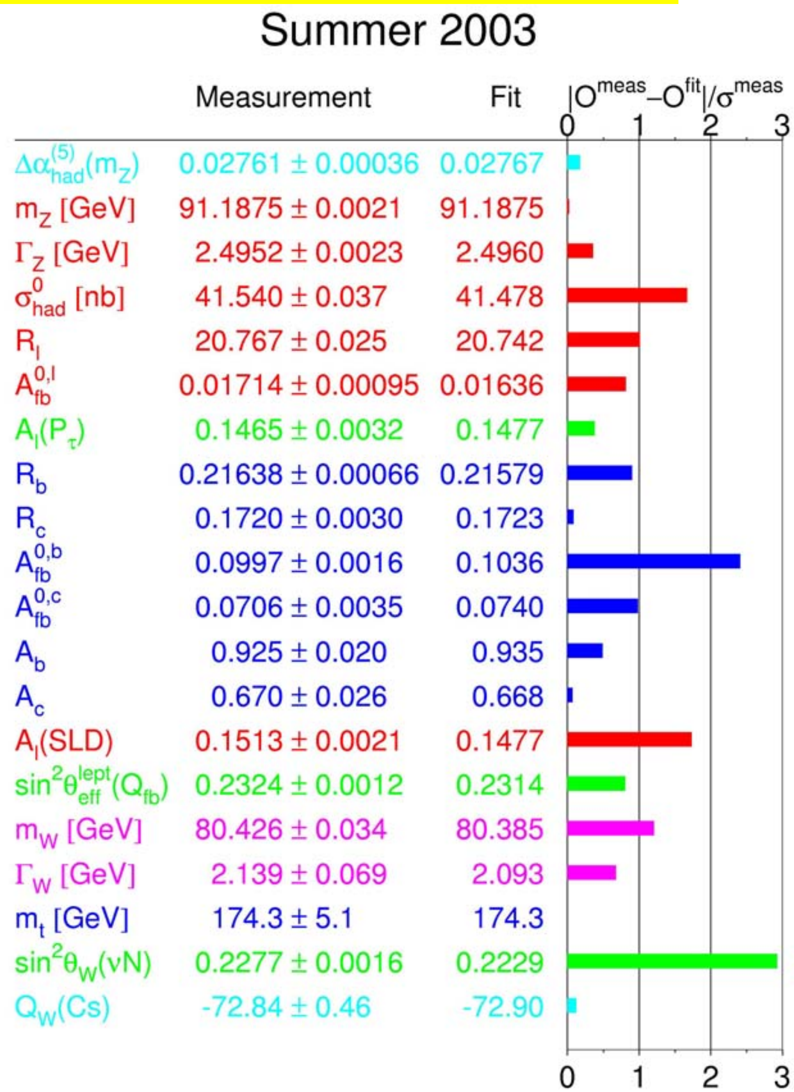

NEW: $M_W$(Aleph) lower, small shifts in heavy flavors, atomic PV close to SM

(new $M_t$ D0 Run I and CDF Run II not included)

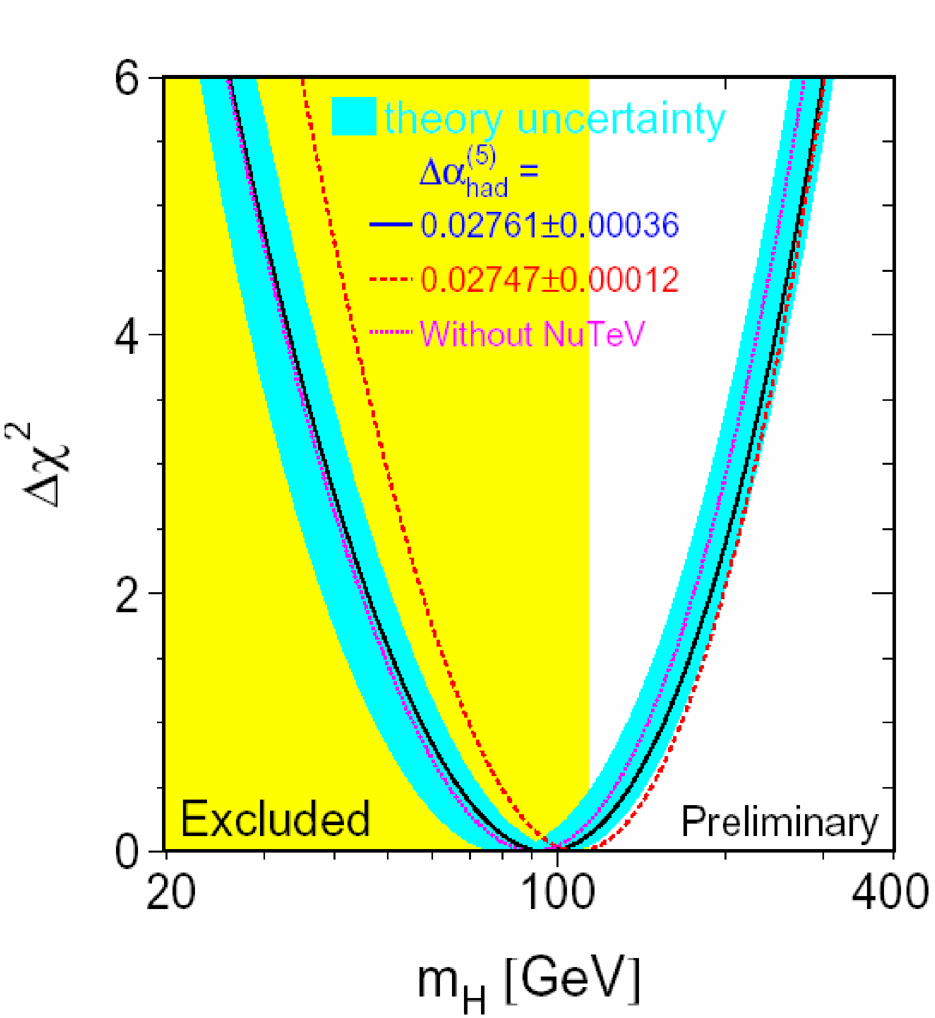
OVERALL, SM fares well

except for NuTeV

(more details in Bob Clare's talk)



# The global EWWG fit



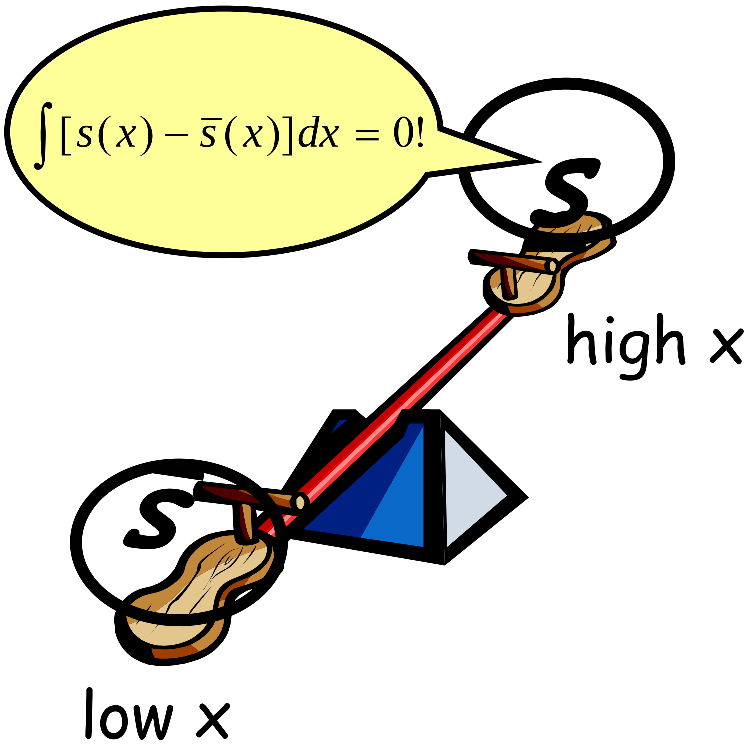

$M_H$=96 GeV, $M_H$<219 GeV at 95%CL
$\chi$ 2/dof=25.4/15 4.5% prob

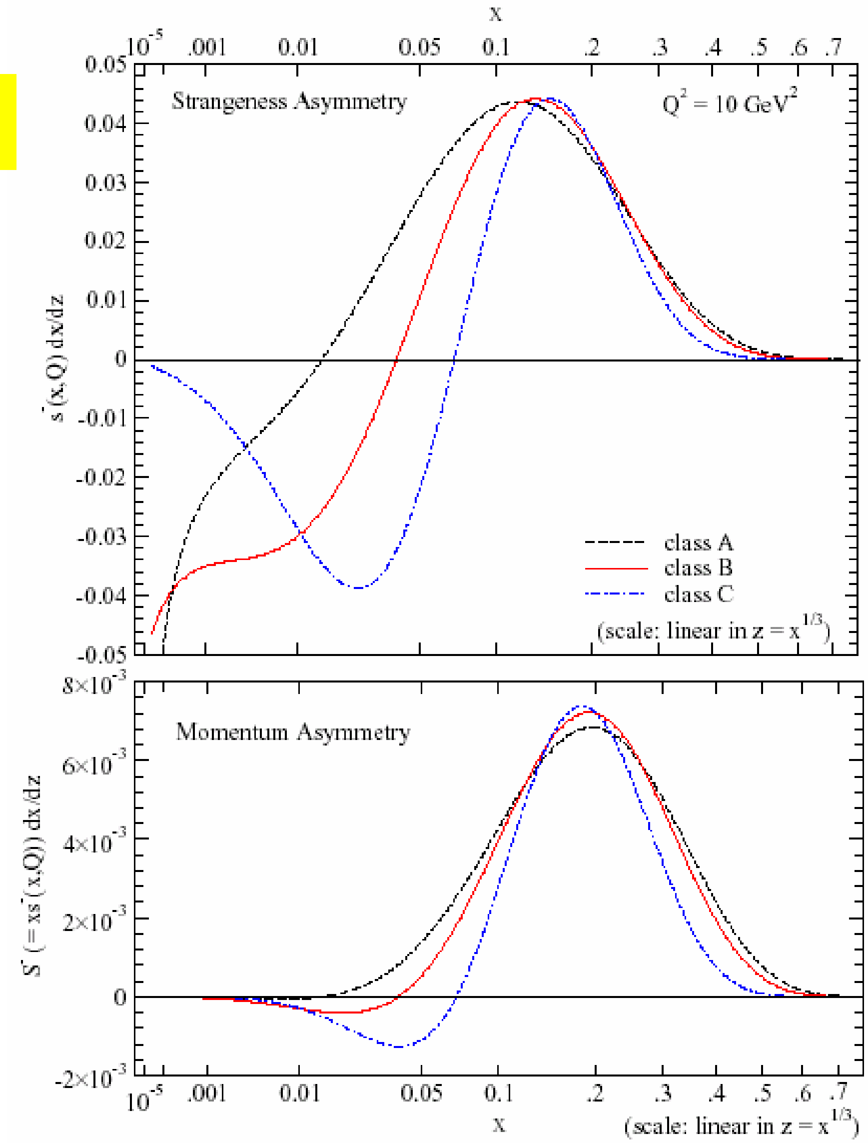
without NuTeV

$M_H$=91 GeV, $M_H$<202 GeV at 95%CL
$\chi$ 2/dof=16.8/14 26.5% prob

$$R_{\rm PW} \equiv \frac{R_\nu - r R_{\bar\nu}}{1-r} = \frac{\sigma(\nu\mathcal{N}\to\nu X) - \sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X) - \sigma(\bar\nu\mathcal{N}\to\bar\ell X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_{\rm W}$$

# NuTeV – Strange Sea Asymmetry?




**Impact on $R_{PW}$ in NuTeV setup estimated w.r.t. to CTEQ s=sbar fit:**

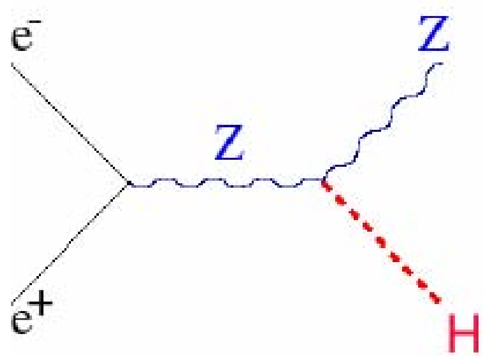
$$0.0012 < \delta_{s2w} < 0.0037$$

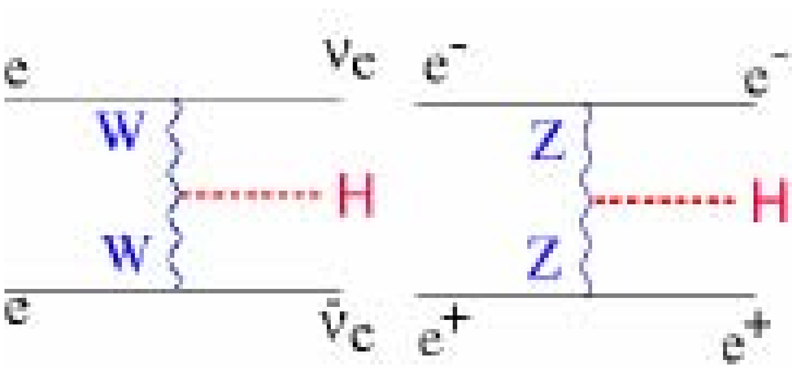
→ reduce discrepancy below 2σ ?

Kretzer, Olness, Pumplin, Stump, Tung et al.

# Higgs Production at LEP

"Higgs-strahlung"

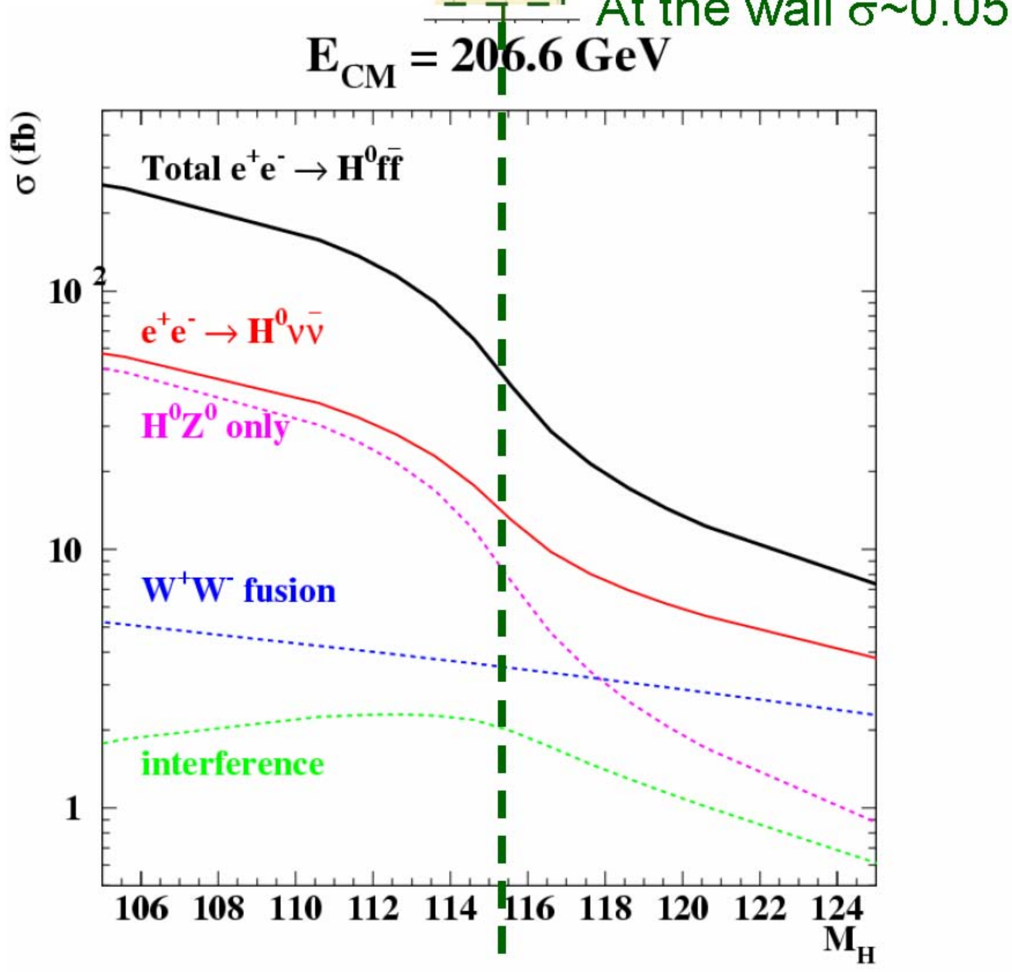


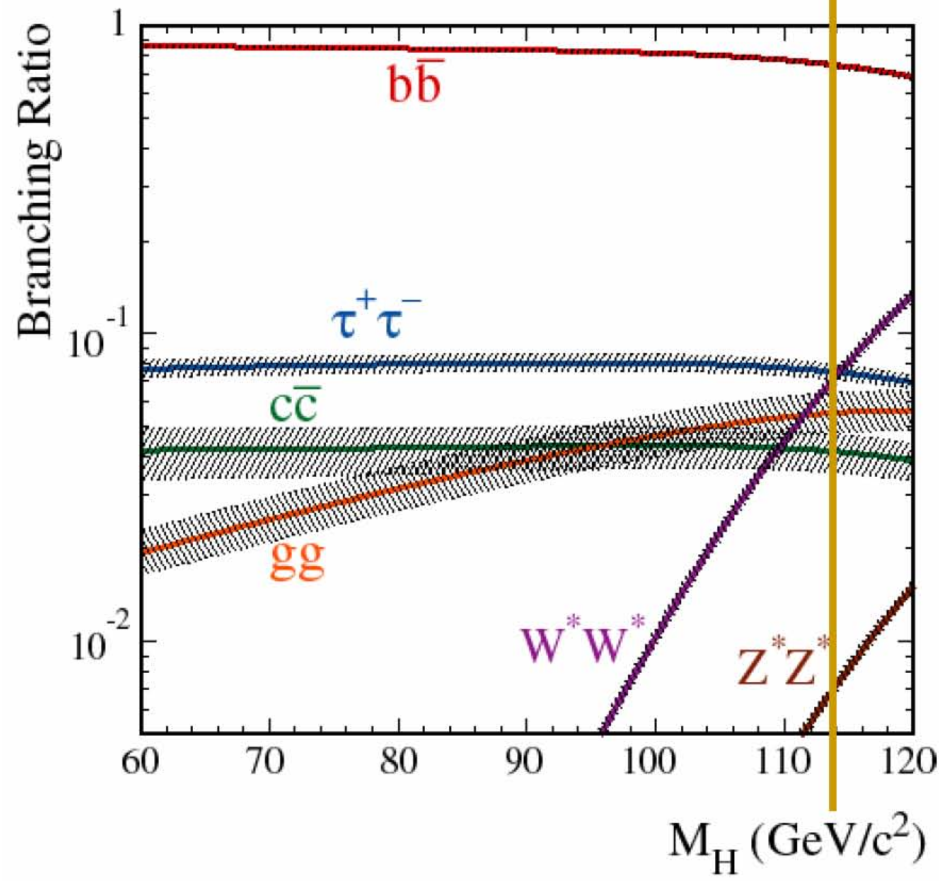

Vector Boson Fusion


=206.6-91.2=115.4

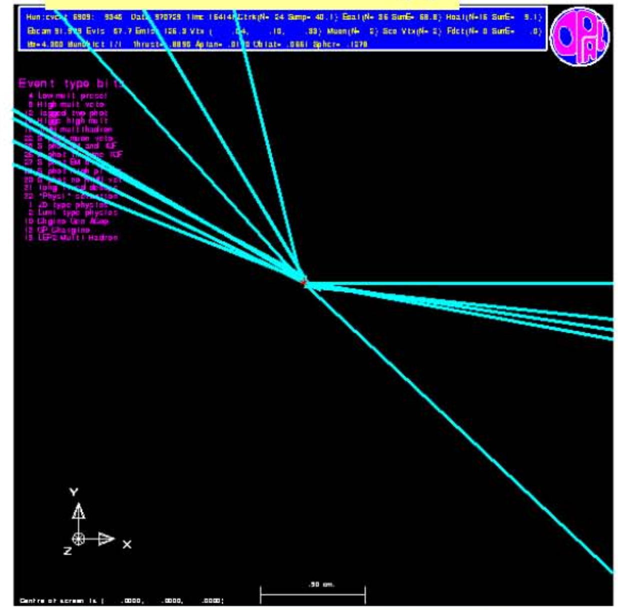
At the wall σ~0.05 pb



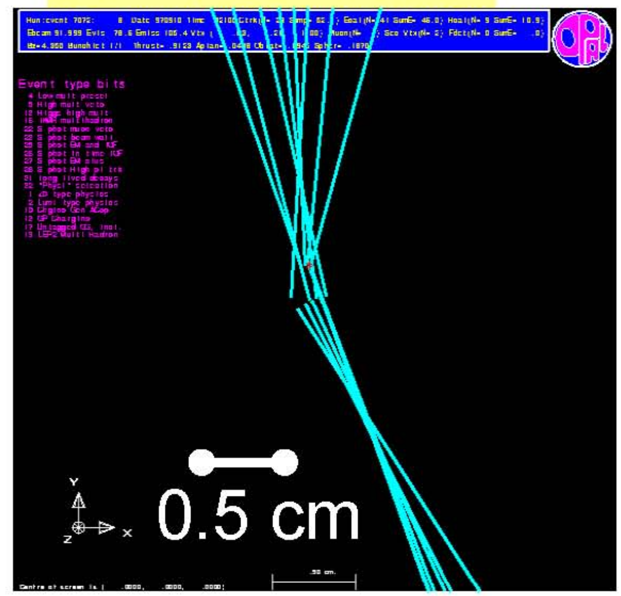
# SM Higgs Decay




$e^+e^- \to ZZ \to \nu\nu q\bar{q}$



$e^+e^- \to ZH \to \nu\bar{\nu}b\bar{b}$

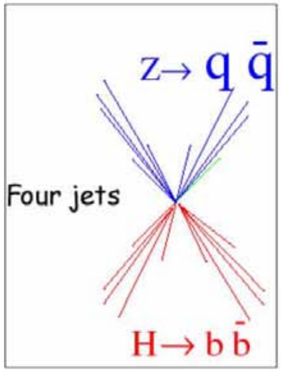



- B-tag is an essential ingredient in Higgs search

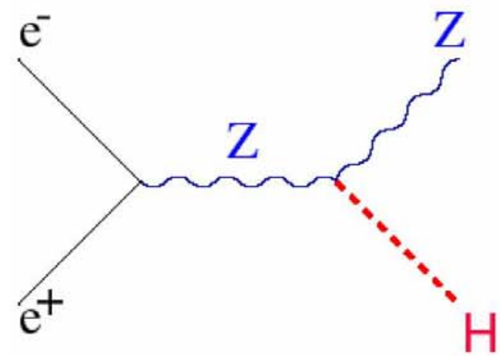
# Higgs Search Channels

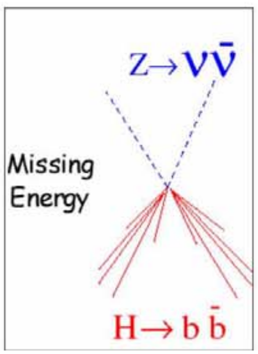
$H \rightarrow b\bar{b}(\sim 75-85\%), \tau^+\tau^-(\sim 8\%)$

$Z \rightarrow q\bar{q}(70\%), \nu\bar{\nu}(20\%),$
$e^+e^- + \mu^+\mu^-(6.6\%), \tau^+\tau^-(3.3\%)$

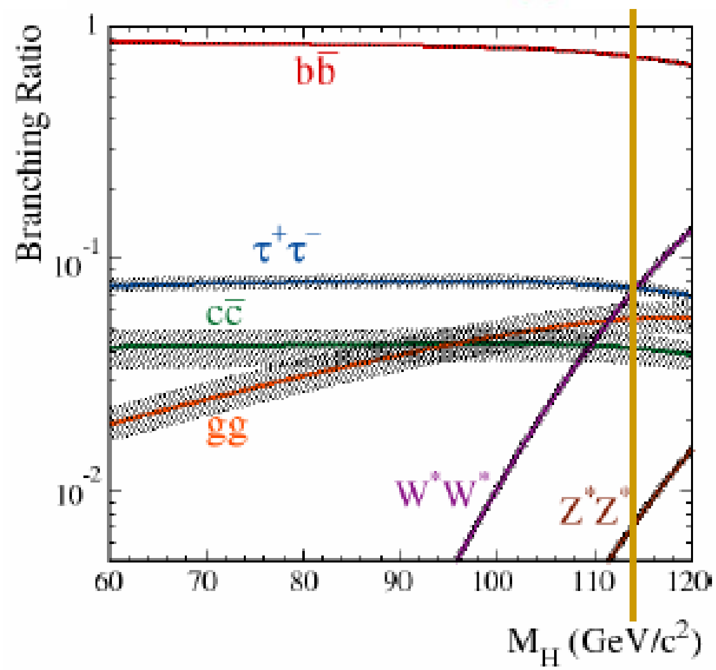


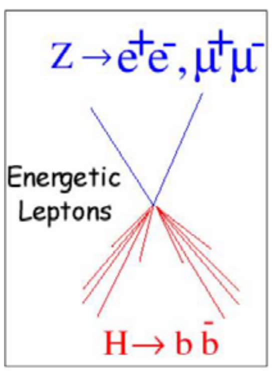

- Energy-momentum conservation
- The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson



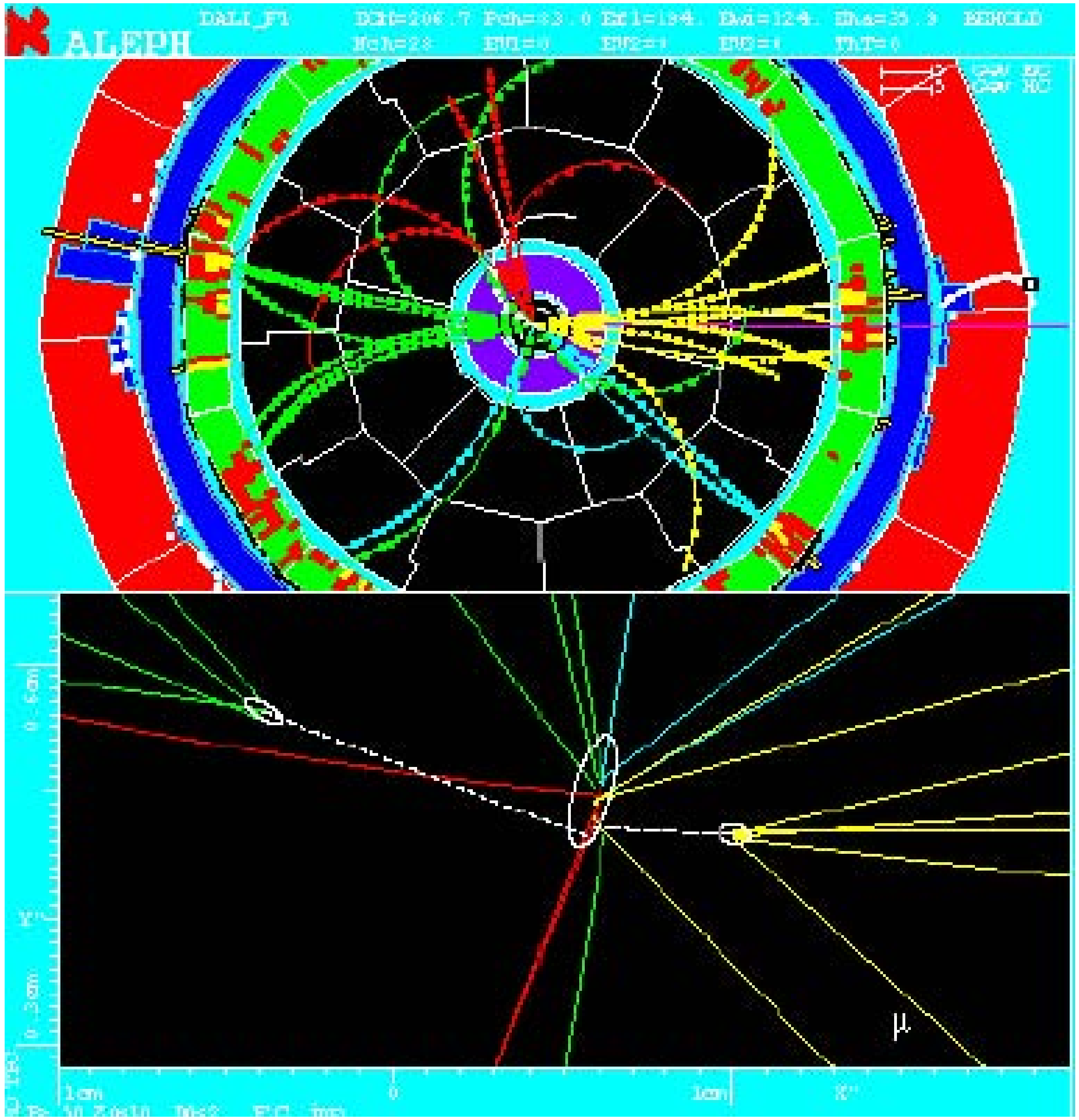

- The recoil mass of the 2 b-tagged jets is compatible with a Z boson




- 2 high energetic leptons with a mass compatible with a Z boson recoil against 2 jets.
- Clean channel

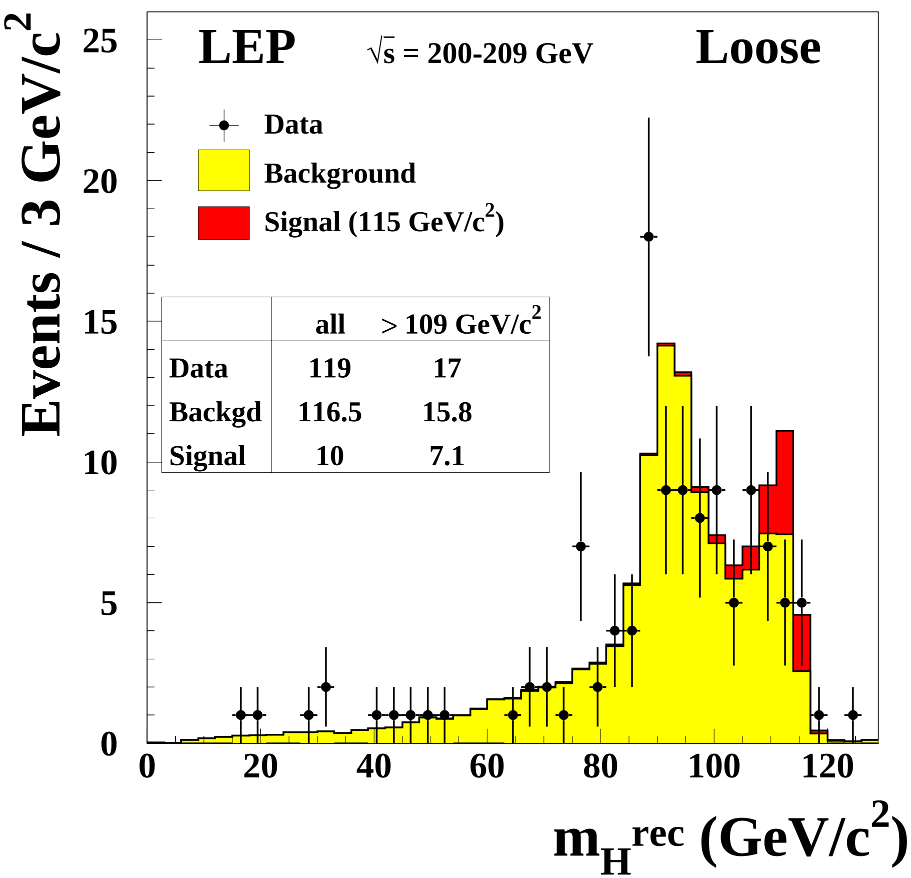
# 4 Jet ALEPH Higgs Candidate (double b-tag)



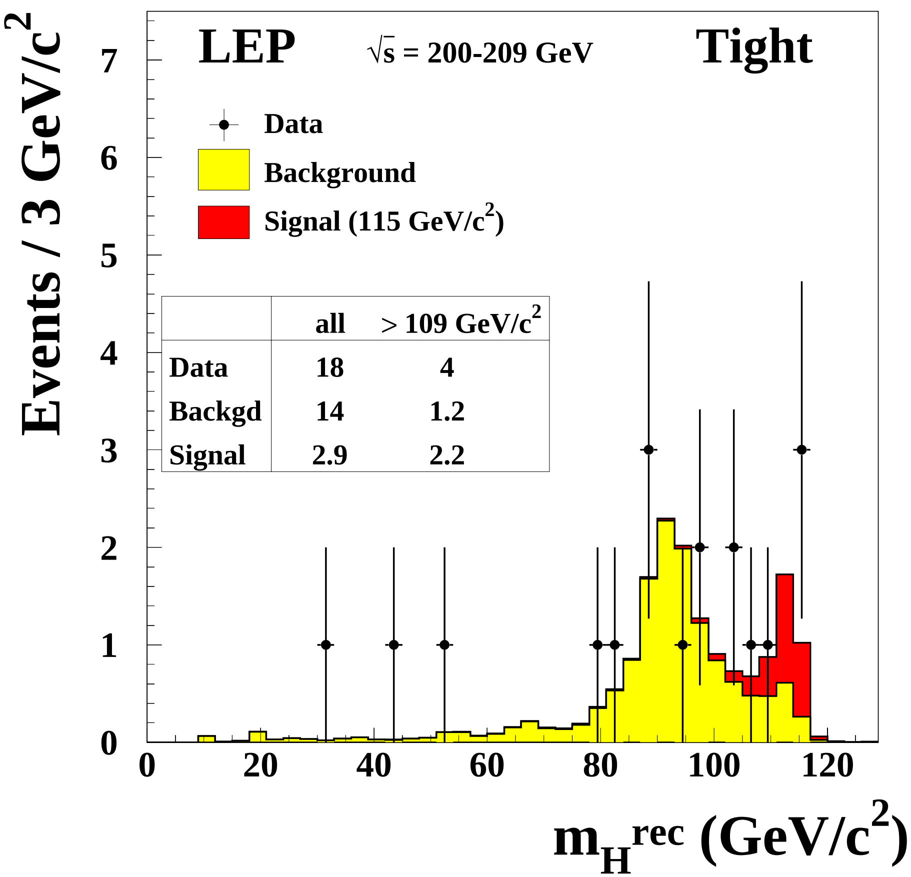
# Reconstructed $M_H$

main background: $e^+e^- \rightarrow ZZ$

low purity selection




high purity selection



# The Statistical Procedure or Ranking Experiments

$$Q = \frac{P_{poisson}(data|s+b)}{P_{poisson}(data|b)} = \frac{L(s+b)}{L(b)} = \frac{e^{-(s_{TOT}+b_{TOT})}}{e^{-b_{TOT}}}\prod_{i=1}^{N_{bins}}\frac{s_i+b_i}{b_i}$$

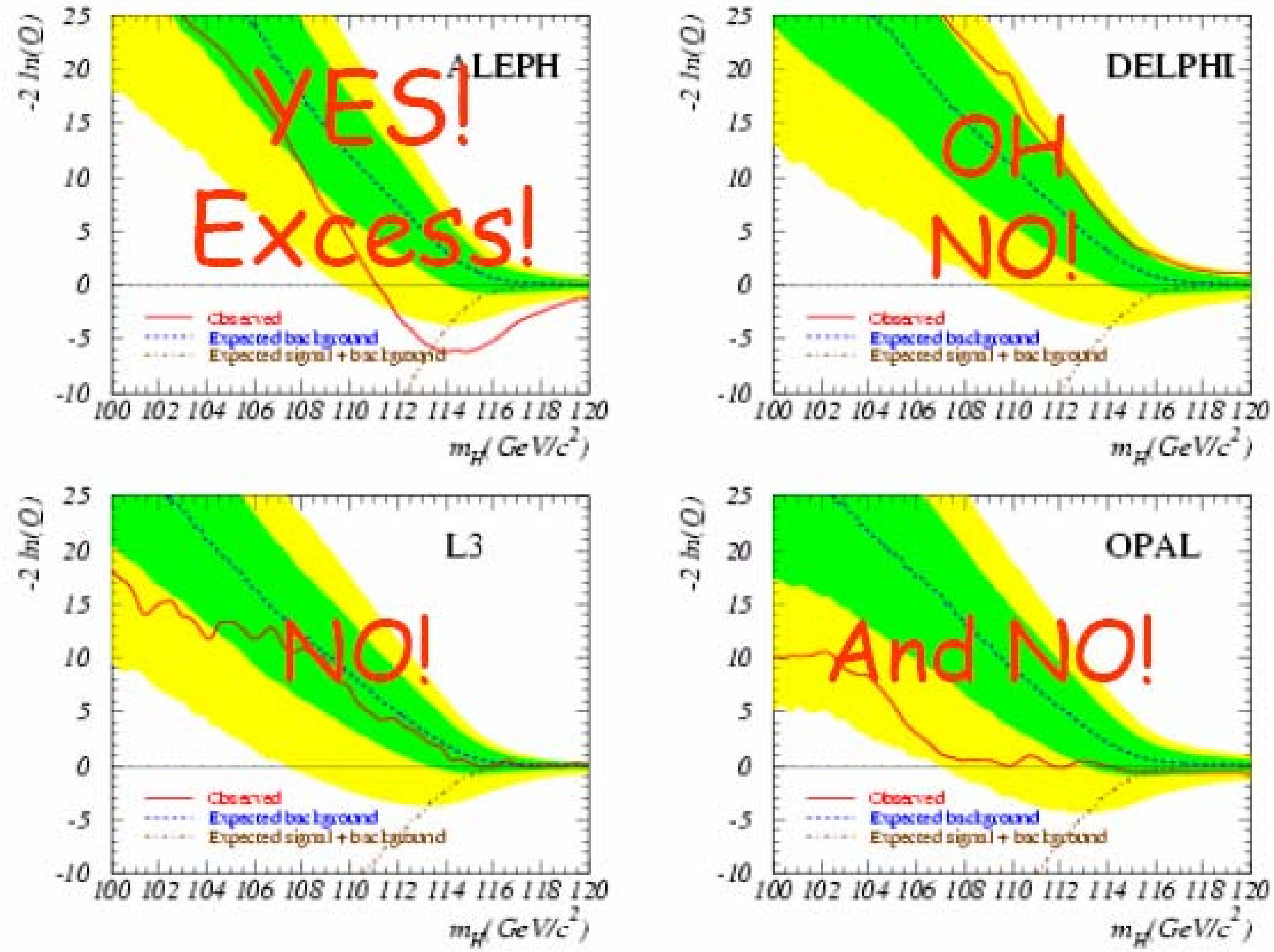
Each observed event is counted with a weight $\ln\left(1+\frac{s_i}{b_i}\right)$

$$-2\ln Q = 2s_{TOT} - 2\sum_{i=1}^{N_{bins}} N_i \ln\left(1+\frac{s_i}{b_i}\right)$$

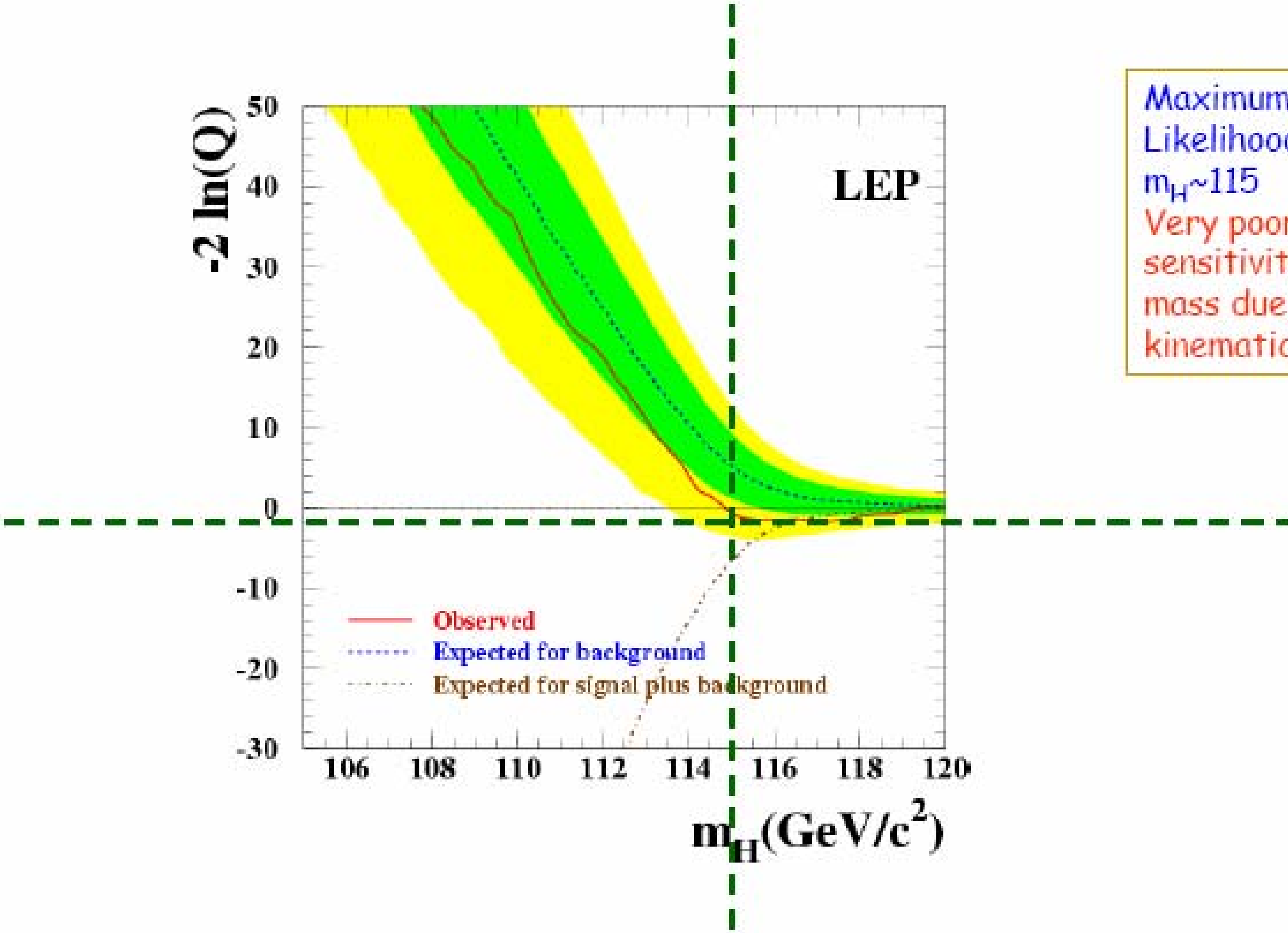
s+b like — - 0 + — b-like -2lnQ

The likelihood ratio, $-2\ln Q(m_H)$ ranks the experimental events configuration between two hypotheses: "s+b"-like and "b"-like,

# The Real Thing: 4 Experiments, 4 Likelihoods



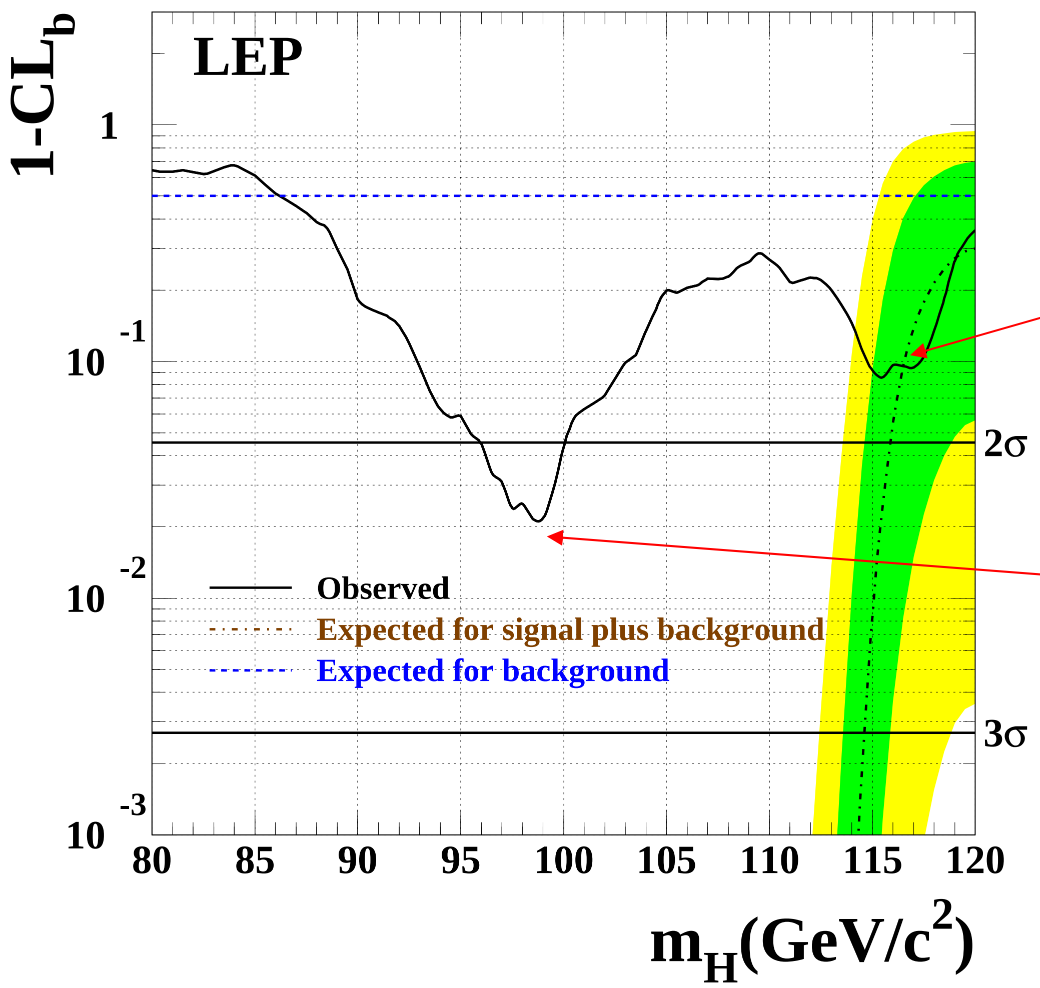
# All 4 Experiments Combined Into One: LHWG




Maximum Likelihood for $m_H$~115
Very poor sensitivity to test mass due to the kinematical wall!

# Higgs Discovery ?

$1 - CL_b$ = prob. to obtain more 's+b like' event config. than observed




compatible with SM Higgs boson **and** with background hypothesis

statistical fluctuation!

S~0.1 SM rate

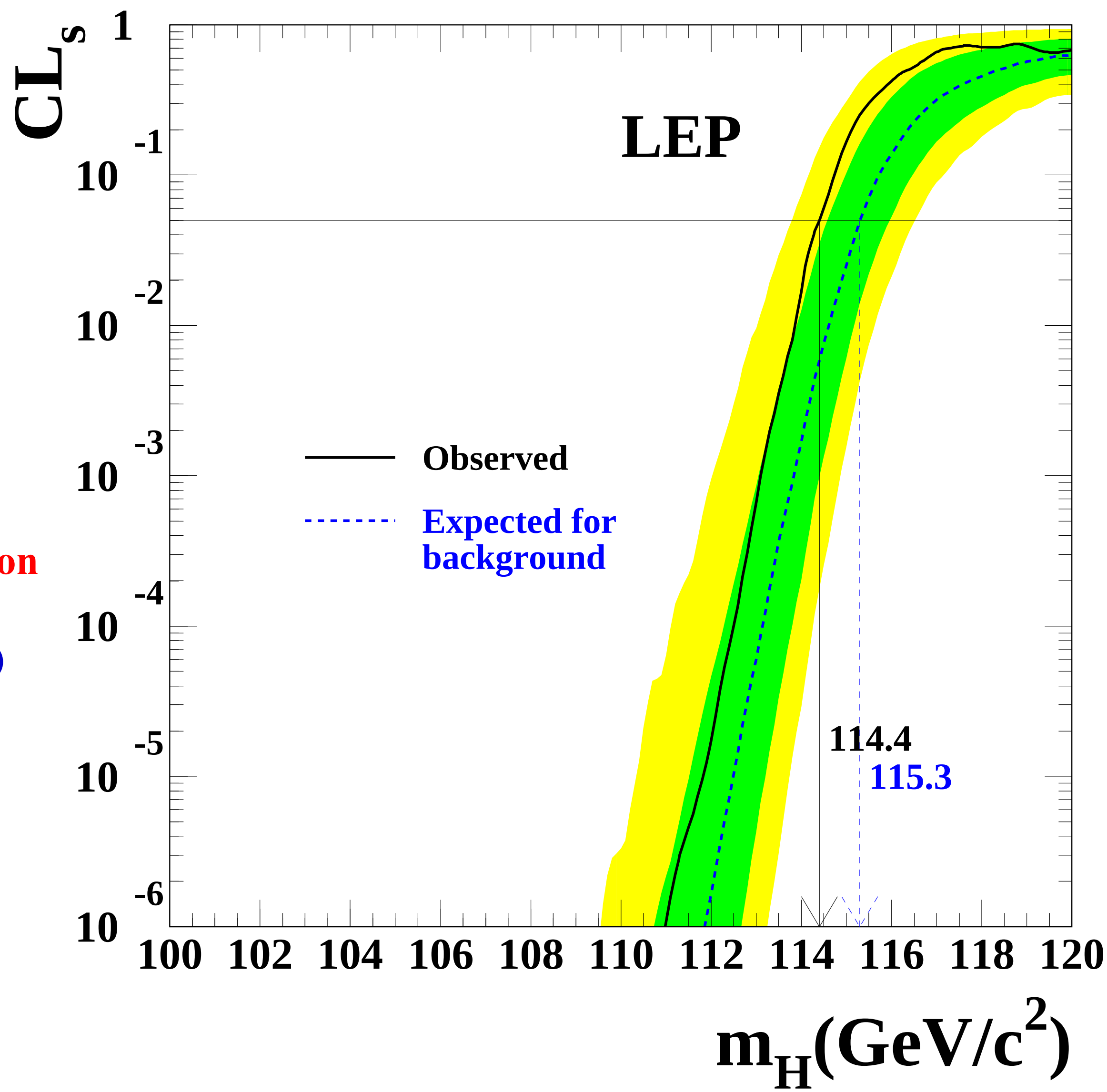
# LEP Higgs Mass Lower Bound

$CL_s = CL_{s+b}/CL_b$

When $CL_s(M_H) < 5\%$ a Higgs boson with a mass $M_H$ is excluded at > 95% CL

LEP excludes a 114.4 GeV Higgs boson

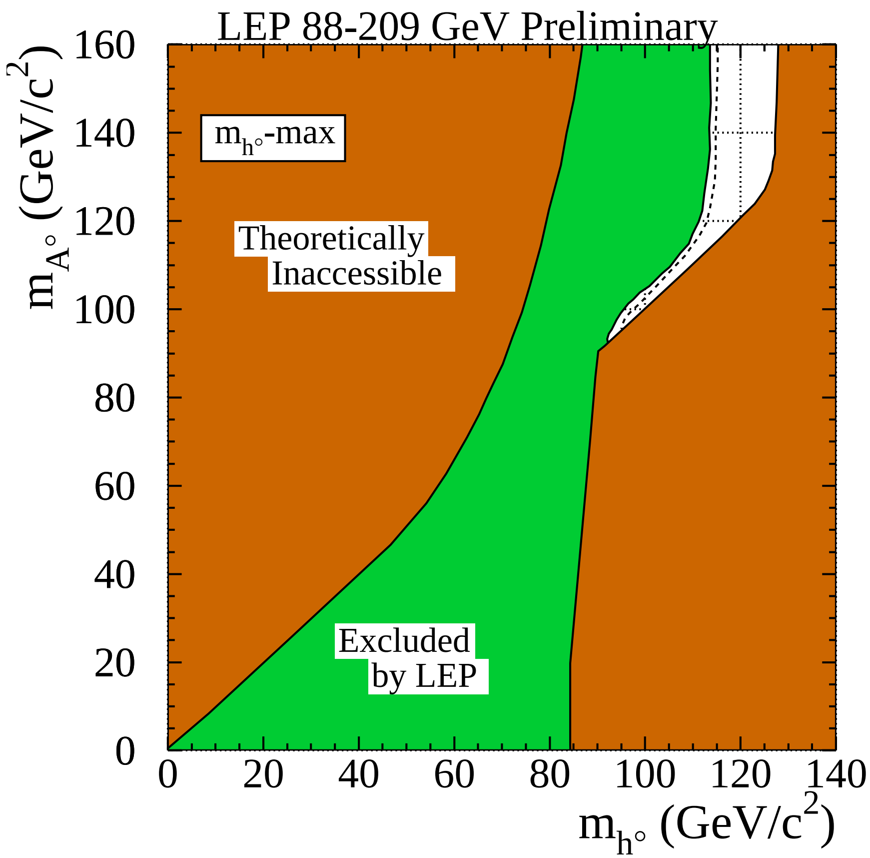
(Expected 115.3 GeV at the 95% CL)

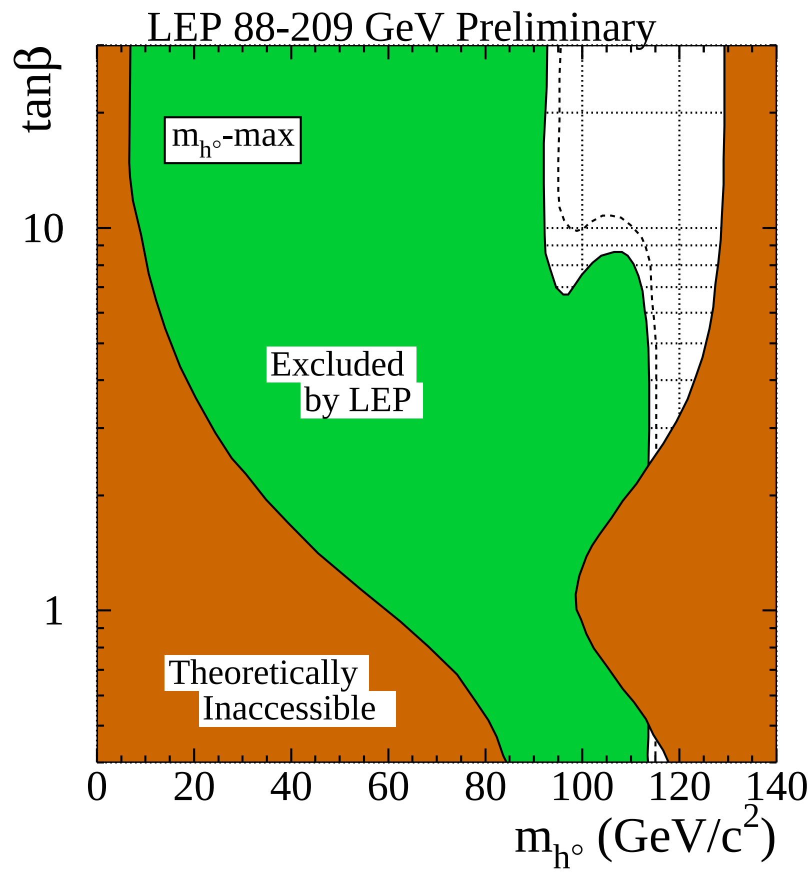


# MSSM Higgs

"$M_h$ – max" benchmark (mSUGRA)

corresponds to most conservative range of excluded tanβ for fixed $M_t$ and $M_{SUSY}$

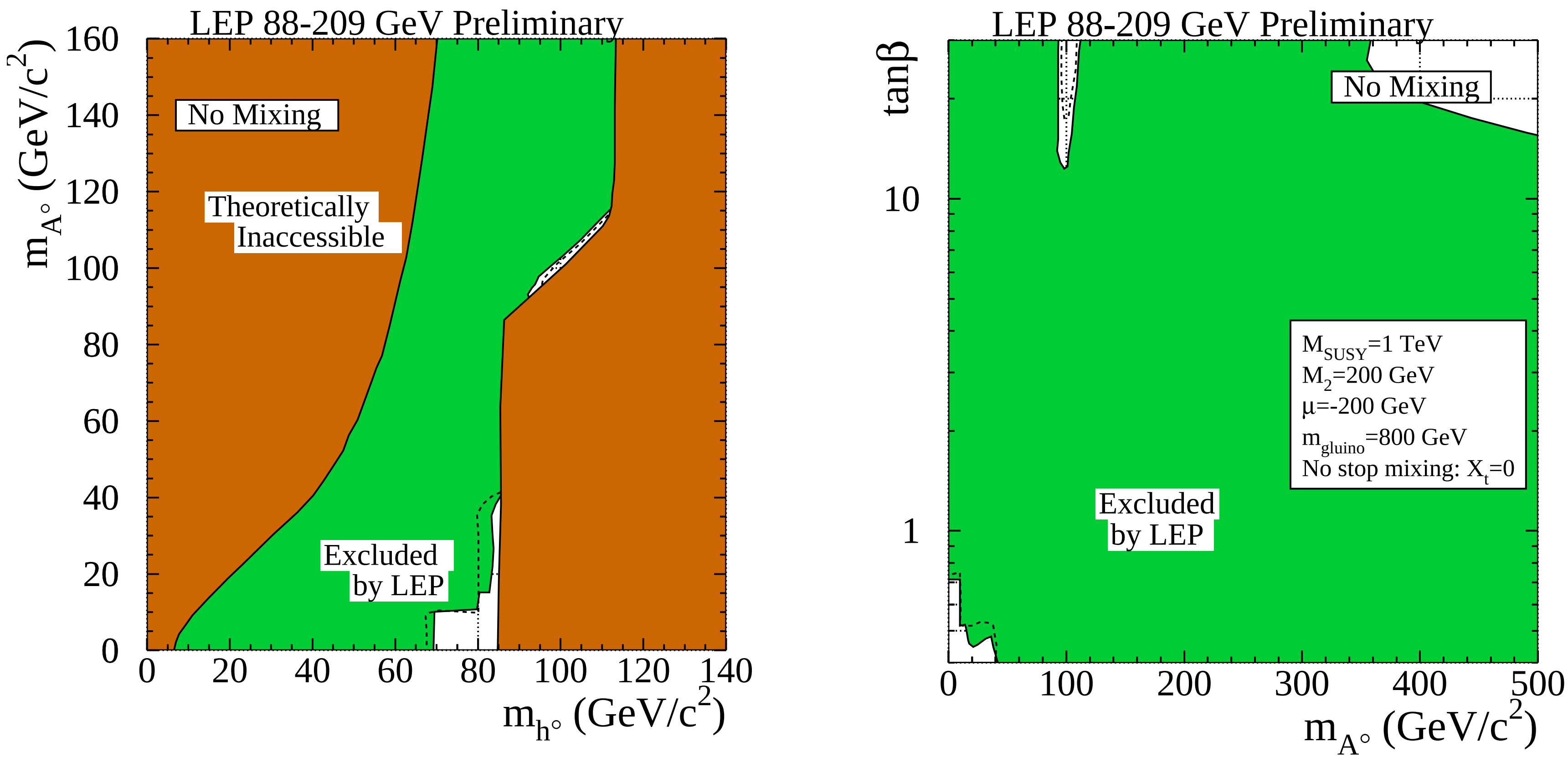


# MSSM Higgs

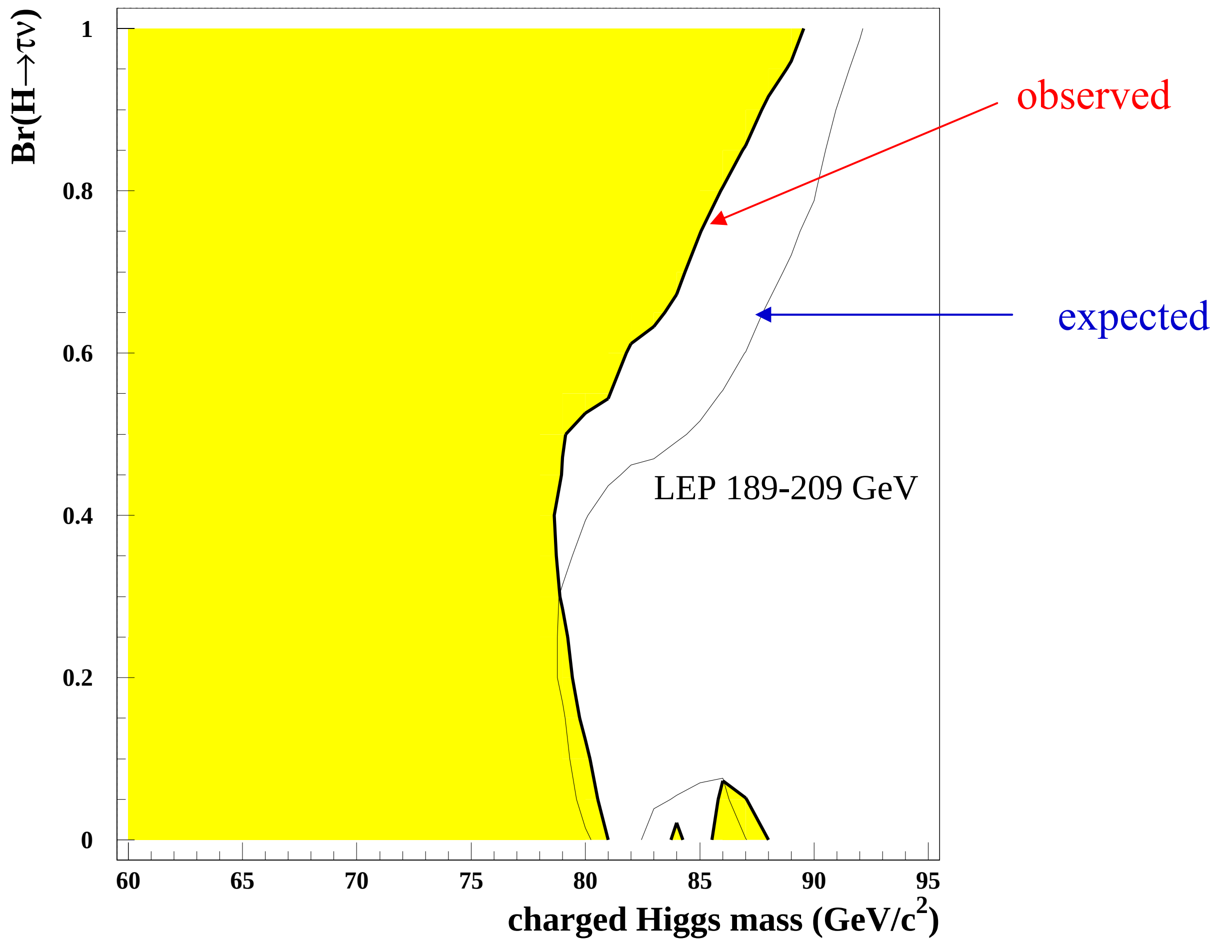
"no mixing" benchmark (mSUGRA)

no mixing between scalar partnres of L and R top quark



# MSSM Charged Higgs

$H^+ \longrightarrow cs$ and $H^+ \longrightarrow \tau\upsilon$

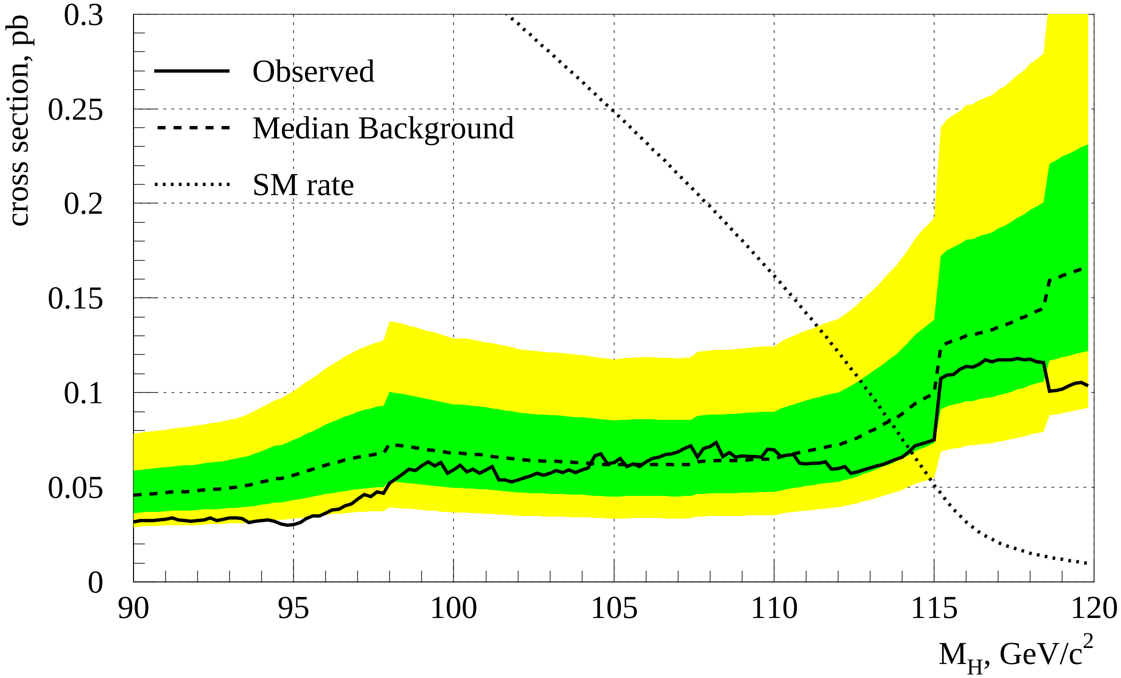


# Invisible Higgs

## Higgs decay to neutralinos or majorons

no significant excess of events observed
- limit set assuming 100% invisible BR

$M_H > 114.4$ GeV (95% CL)



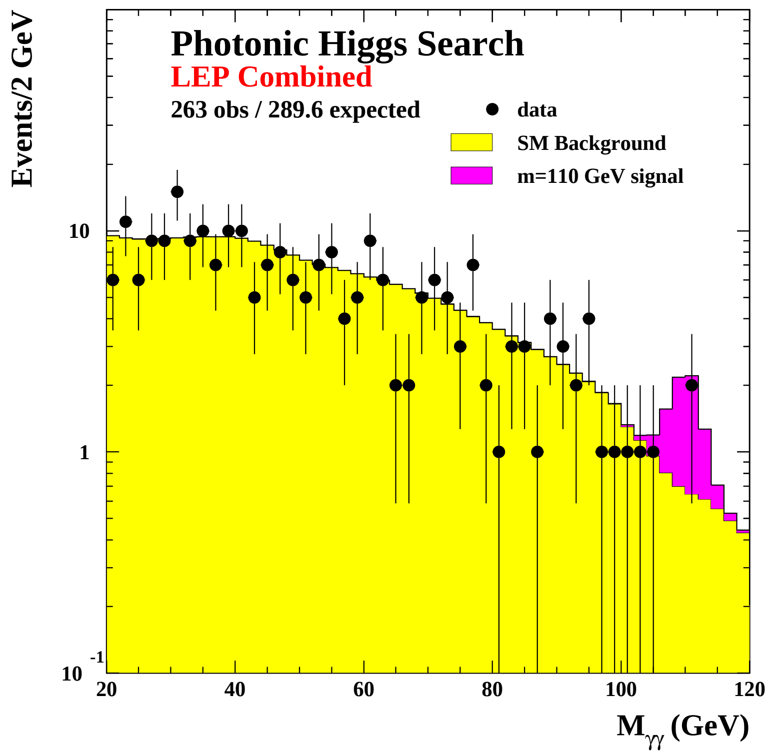
# Fermiophobic Higgs

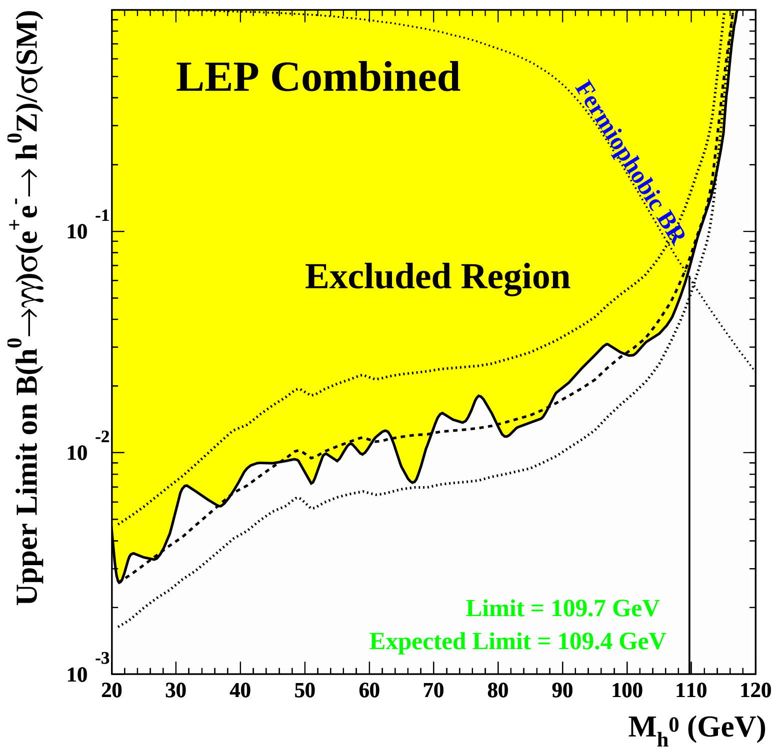
SM BR(H→γγ) too small for observation at LEP

in some 2 Higgs doublet models, Higgs coupling to fermions is very small and Higgs decays preferentially to bosons

(Akeroyd 1996, Brucher/Santos 2000)

$M_H > 108.2$ GeV (95% CL)

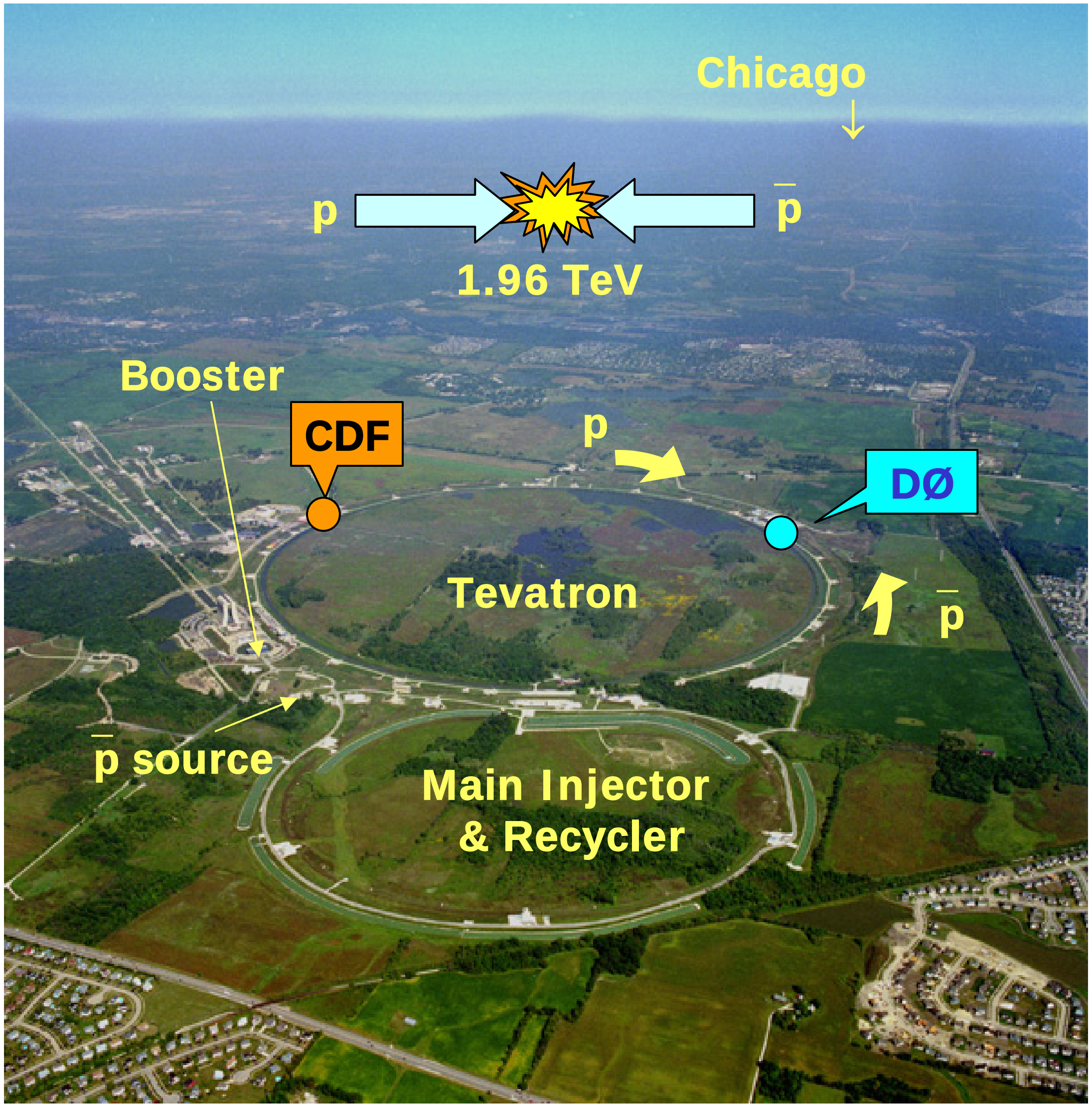


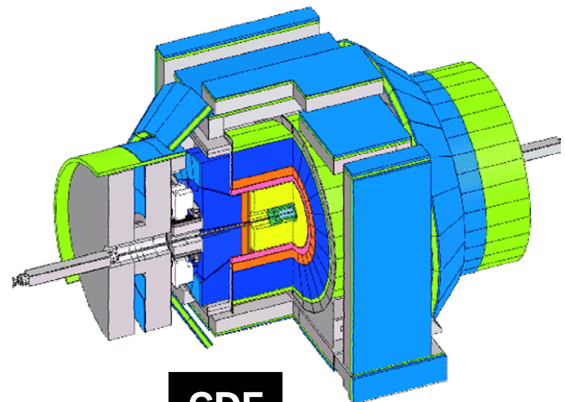



# The LEP Legacy

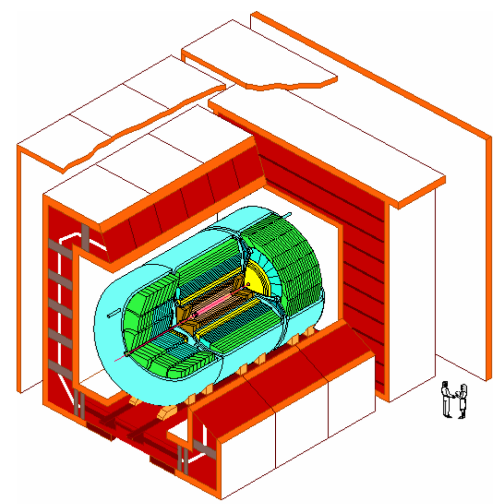

Claus Grupen (2000)

# Higgs at the Tevatron ?



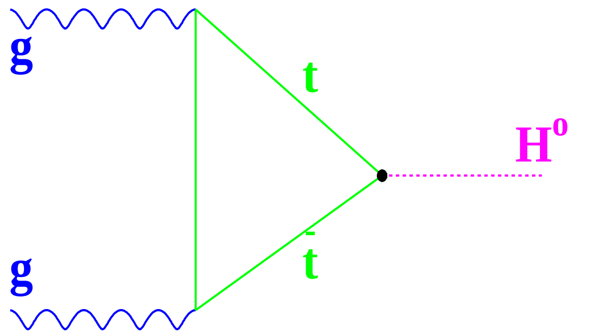
CDF



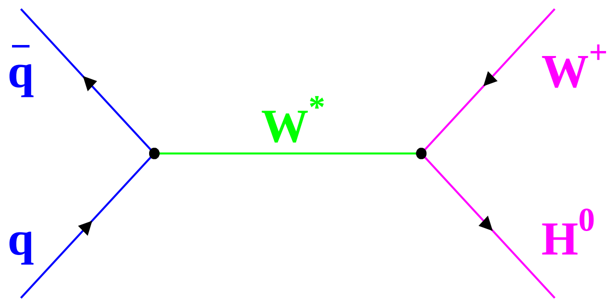
DØ

# Higgs Production Cross-Sections

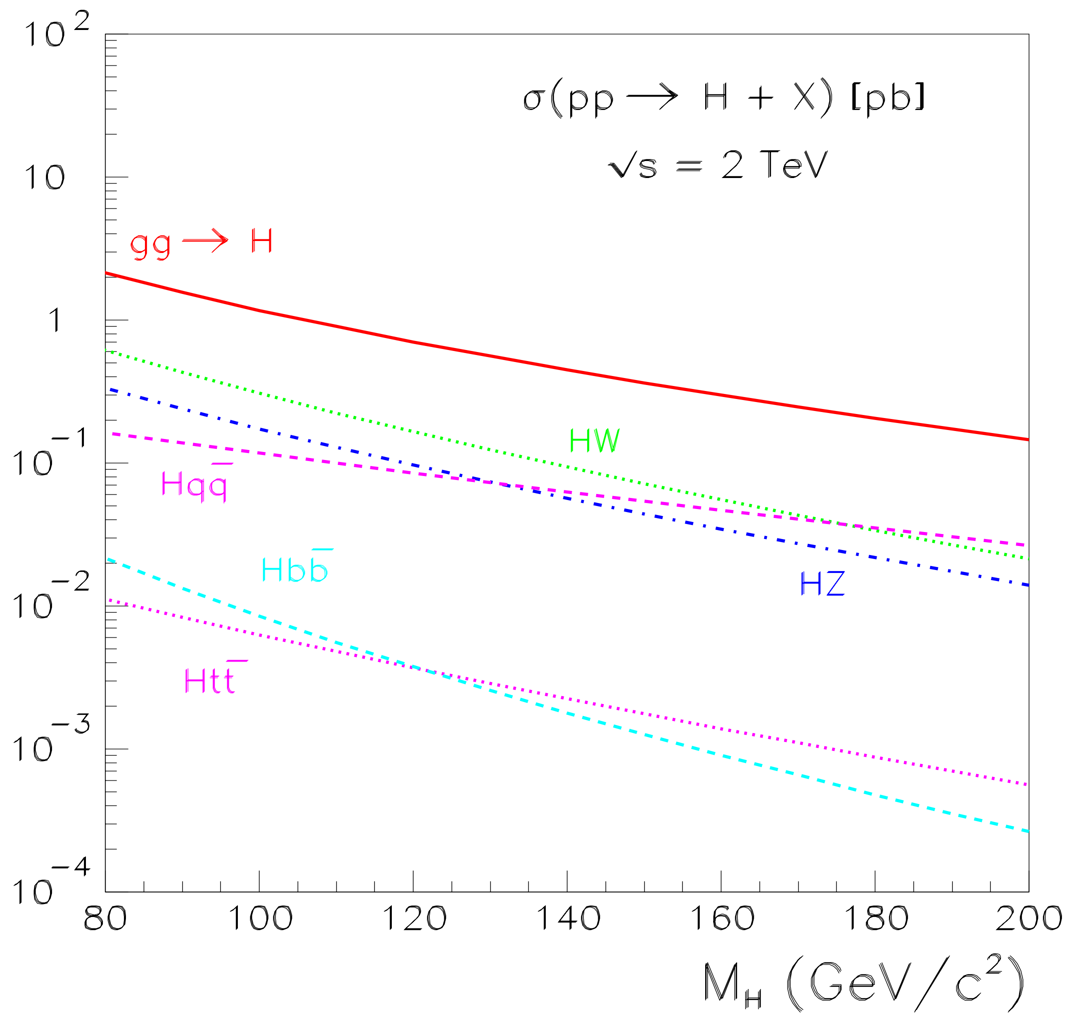
Gluon fusion dominates but WH/ZH production more accessible ...



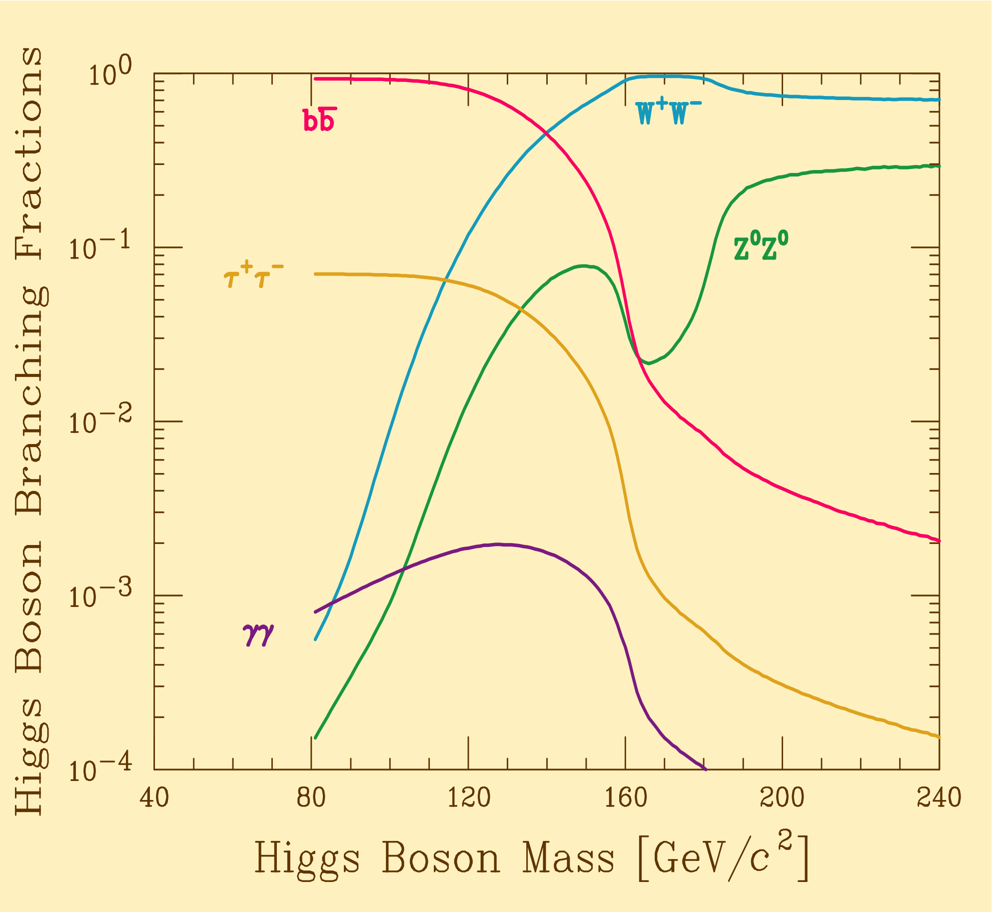

Gluon fusion




Associated production
WH or ZH



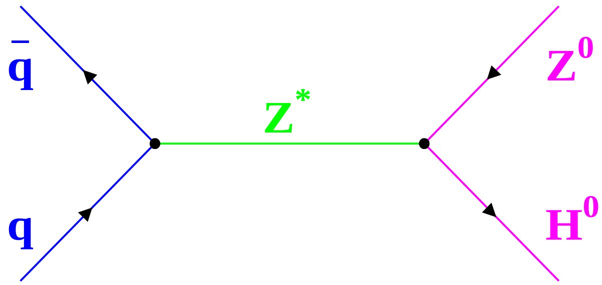
# Higgs Decay Branching Ratios

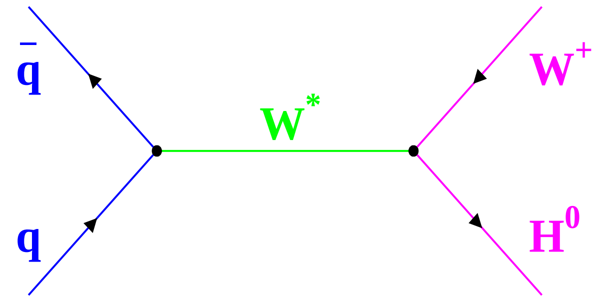



- For $M_H \leq 135$ GeV
  - $H^0 \to b\bar{b}$ dominates … but rate falling rapidly
  - QCD background precludes $gg \to b\bar{b}$
- For $M_H \geq 135$ GeV
  - Gauge boson decays dominate ( $H^0 \to WW^*$ )
  - exploit large gg cross-section

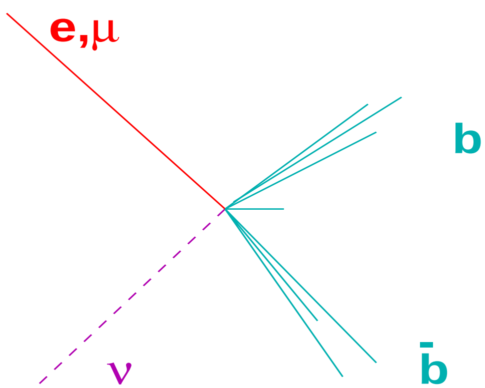
# Tevatron: low mass Higgs searches

For $M_H \leq 135$ GeV: use the same basic strategy as LEP …
… study associated production of ZH *and* WH




To the standard leptonic HZ channels add $W \rightarrow l\,\nu$ with $H \rightarrow bb$ ...



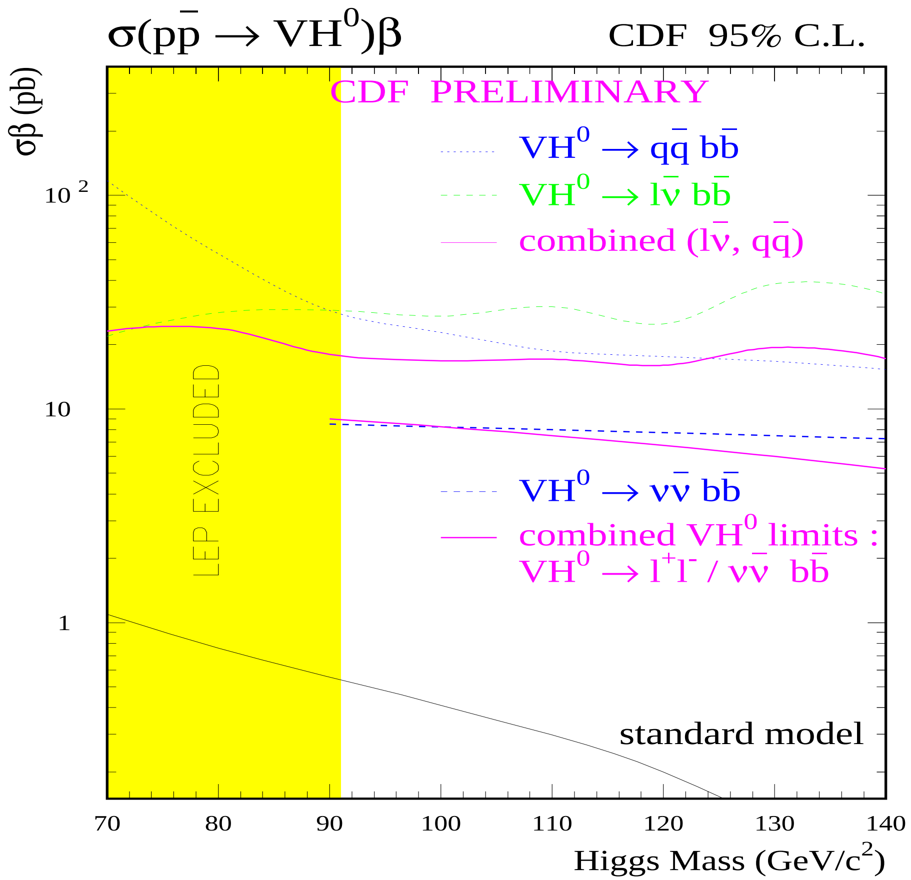

… the qqbb channel is *very* difficult as the QCD backgrounds are severe

Low mass Higgs sensitivity depends on

- the integrated luminosity collected
- b-quark jet tagging performance
- mass resolution of reconstructed bb jets

# SM Higgs searches in Run I

CDF SM low mass Higgs searches ...

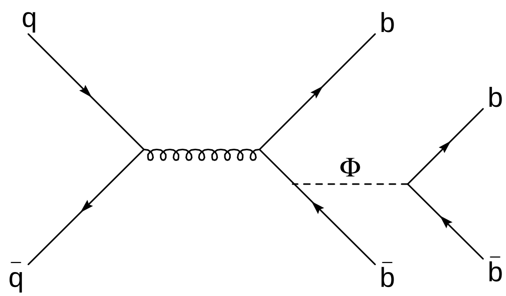


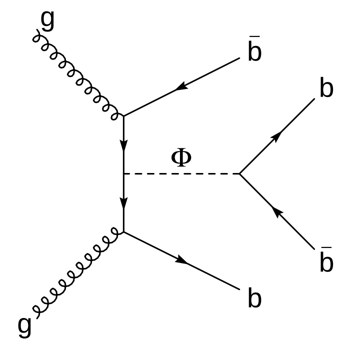

… similar results from DØ for lνbb

# MSSM Higgs searches in Run I

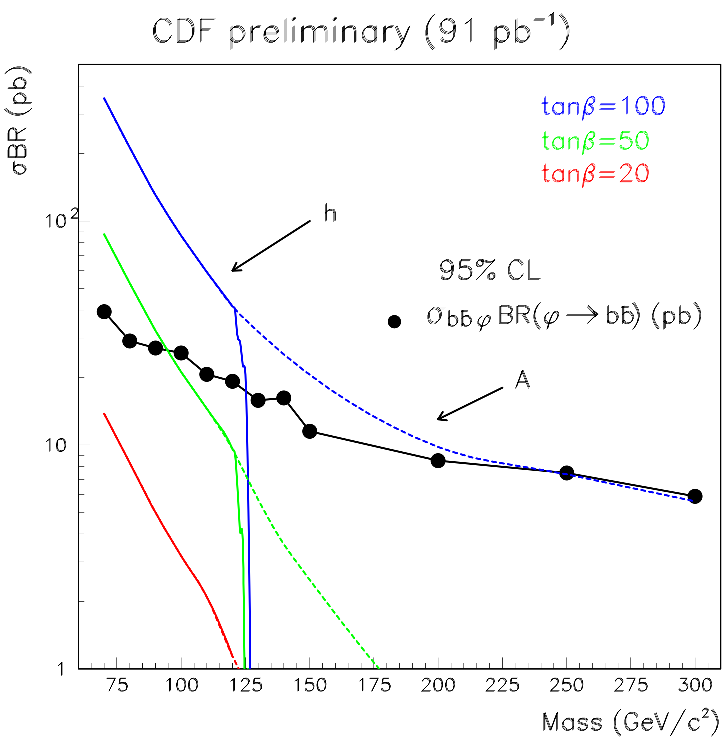
Large bb cross-section at the Tevatron can be used to exploit enhanced Yukawa couplings e.g. Abb coupling $\propto \tan\beta \Rightarrow$ cross-section $\propto \tan^2\beta$

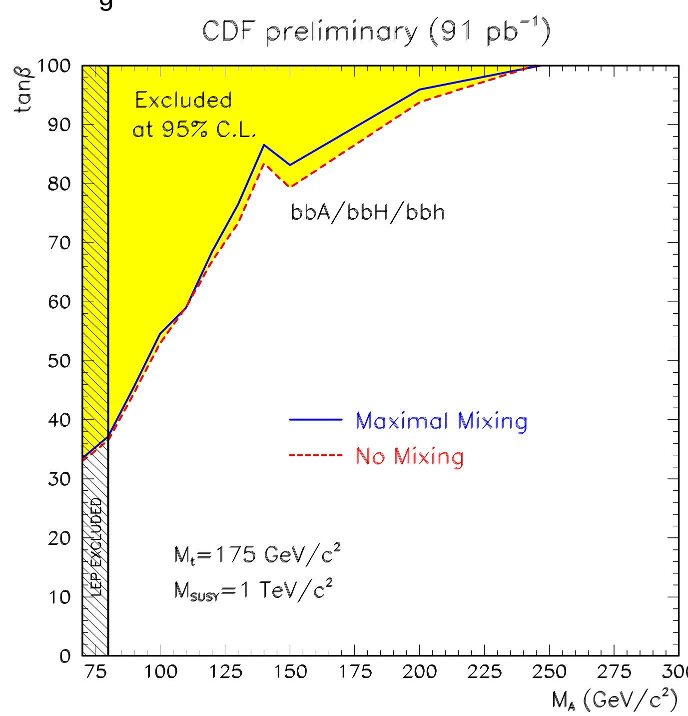
$\therefore$ search for bb$\phi$ production where $\phi$ = h, H, A




$\bar{b}$



# Tevatron: high mass Higgs searches

$M_H > 135$ GeV

$H \rightarrow VV$ (V=W,Z)

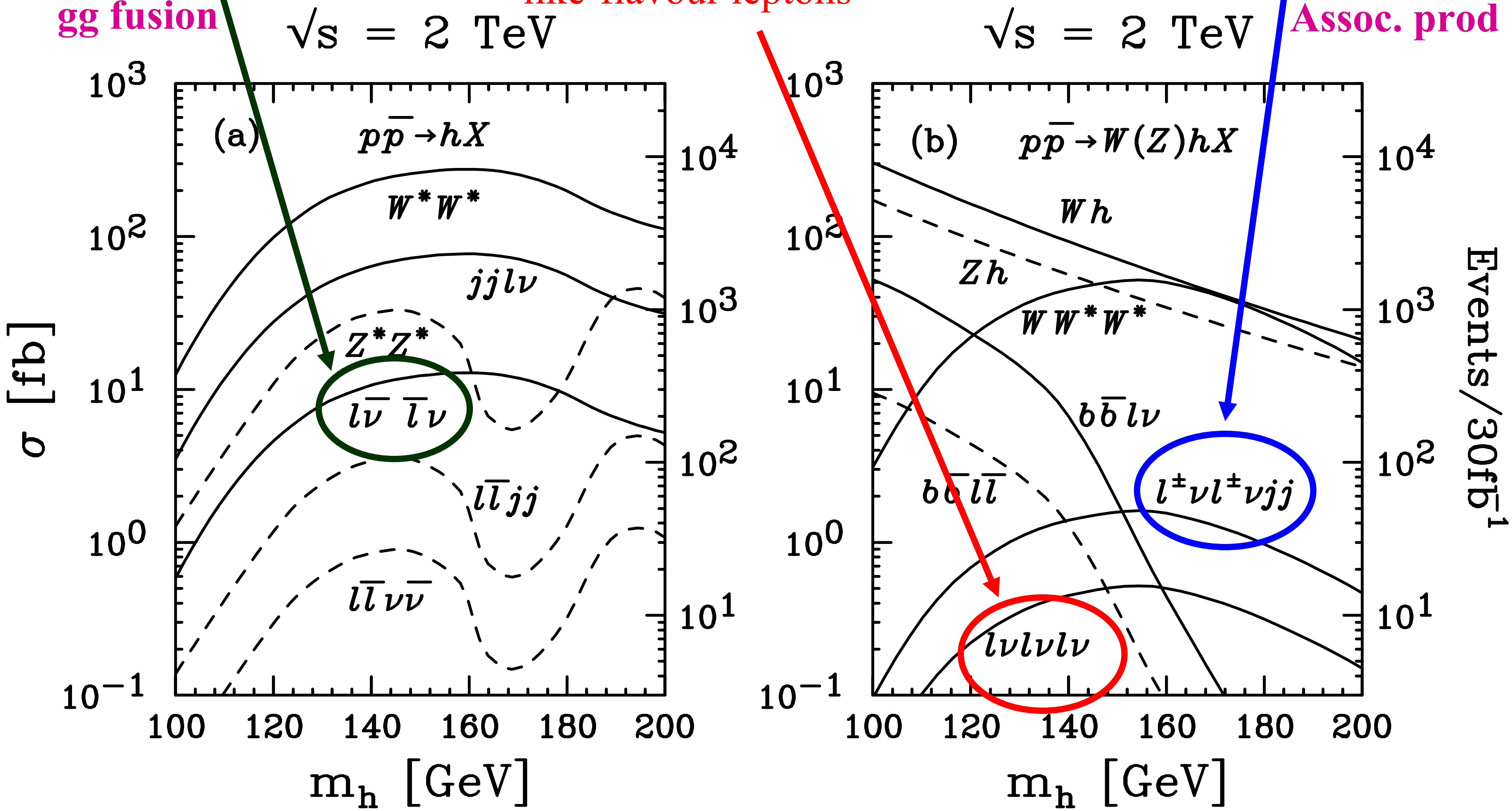
Dileptons + $\not{E}_T$
~ large SM bgnds
(VV, tt, ττ, tW)

Trilepton final states
~ low bgnds but **small** rate
*Golden Modes:* like-sign, like-flavour leptons

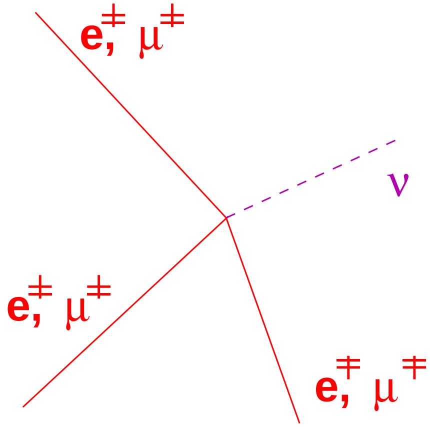
Like sign dileptons + jets
~ many SM bgnds
(VVV, Vtt, VVjj, tt, Vjjj)

gg fusion

Assoc. prod



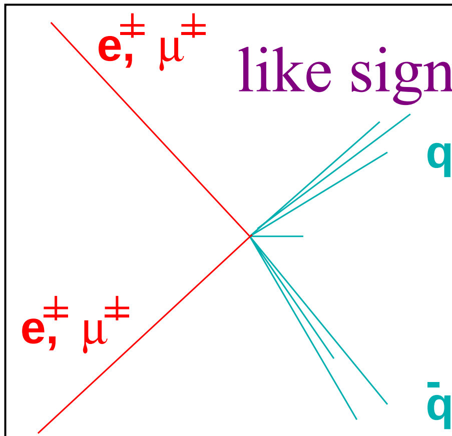
# High mass Higgs




## trileptons

very low SM rate
- sensitive to new physics!

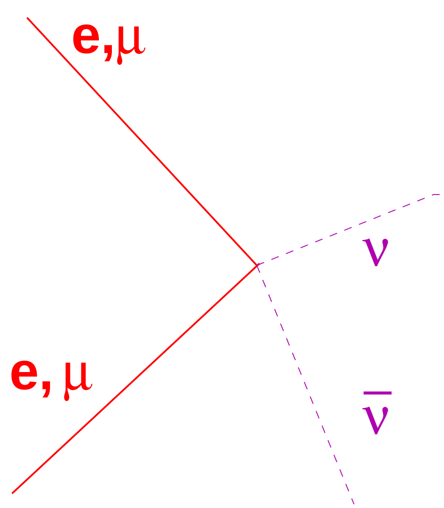
## like sign dileptons + jets

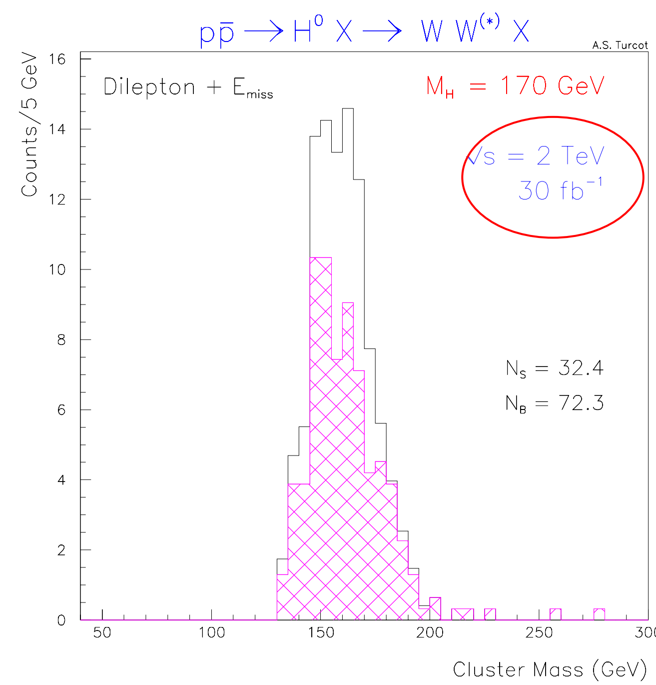



standard new physics search topology
- many backgrounds

## dileptons + missing $E_T$

use kinematic and angular info to suppress backgrounds

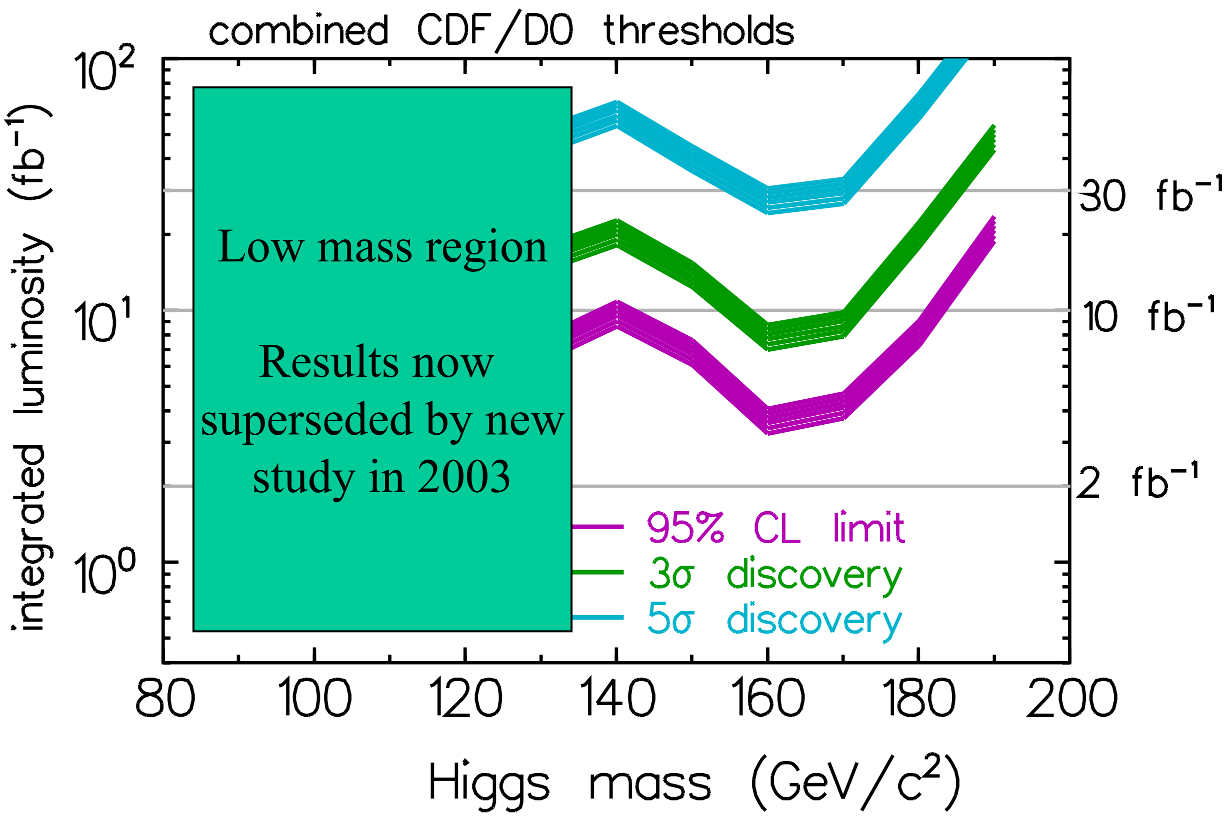


# High mass Higgs discovery potential

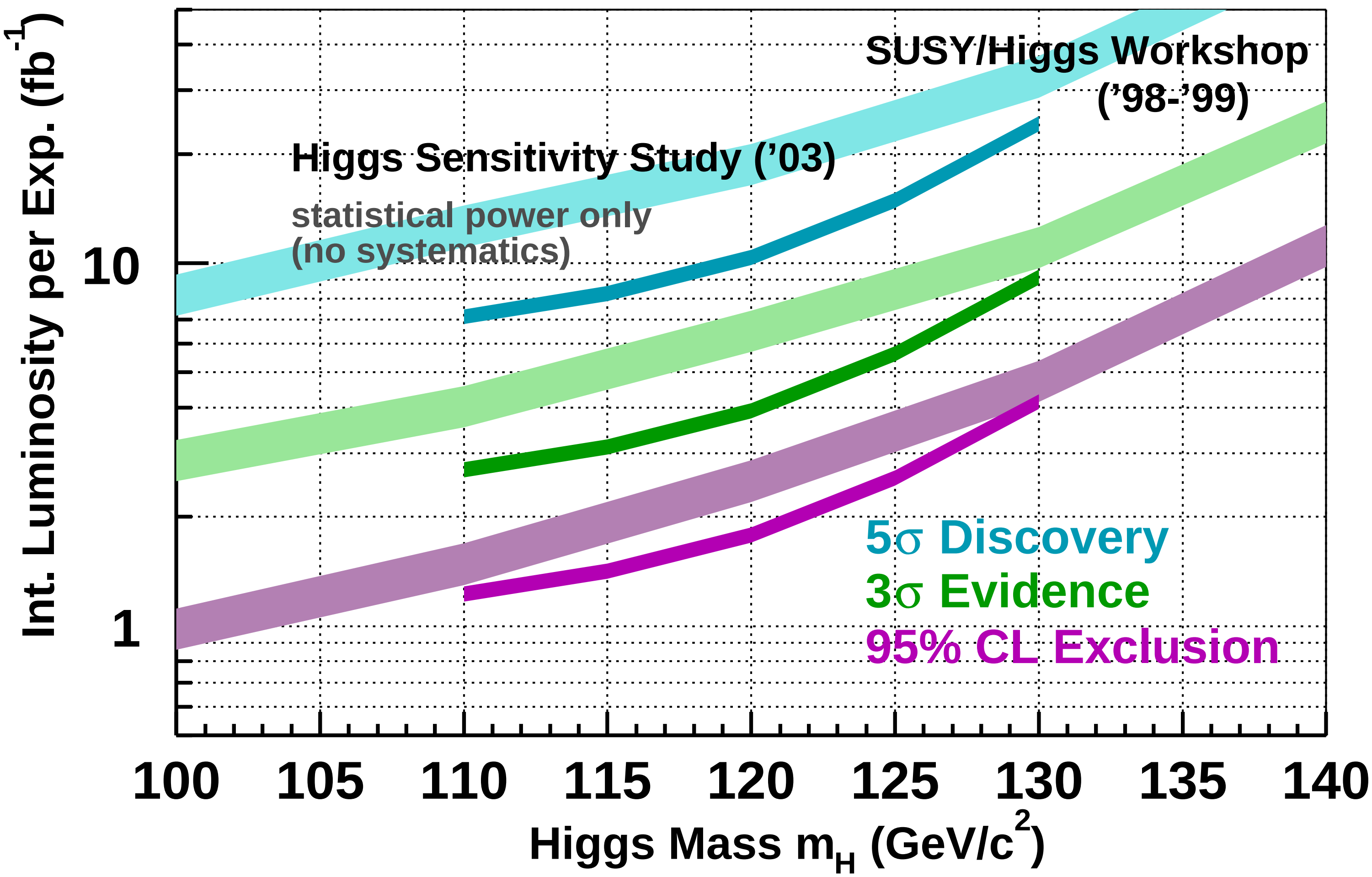
… based on 'old' CDF/D0 study in 1999/2000

generic detector simulation, old cross-section calculations, …




**For 10 inv fb: 95% exclusion for 140-185 GeV, but little discovery potential**

# Low mass Higgs revisited (2003)



# Higgs background processes at the Tevatron

Need to understand:-

- W/Z boson production (+jets)
  - VV
  - V + 2 jets
  - VVV
  - VV+2 jets, V+3 jets
- top production
  - tt pairs
  - single top
  - Vtt
- Drell-Yan pairs ($qq \rightarrow \gamma^* \rightarrow ee, \mu\mu, \tau\tau$)
- QCD jets
- ...

Low and high Higgs masses

Can investigate these background processes:

- theoretically
- experimentally
- both (ideally)

# What would we like from theory ?

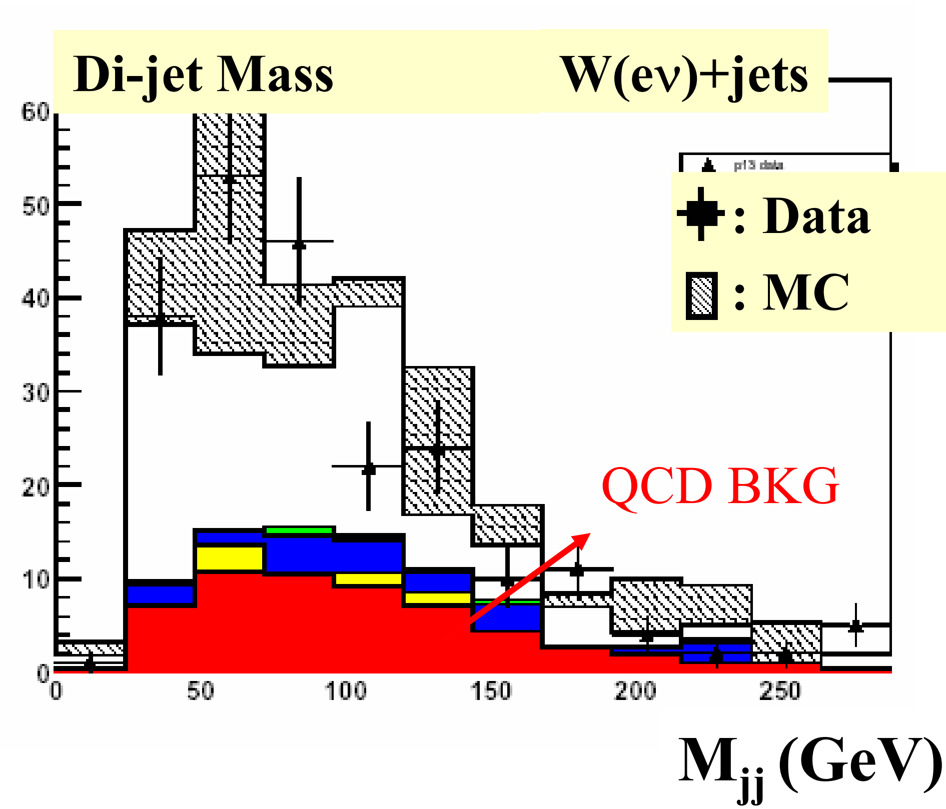

Bruce Knuteson's wish-list from the Run 2 Monte Carlo workshop

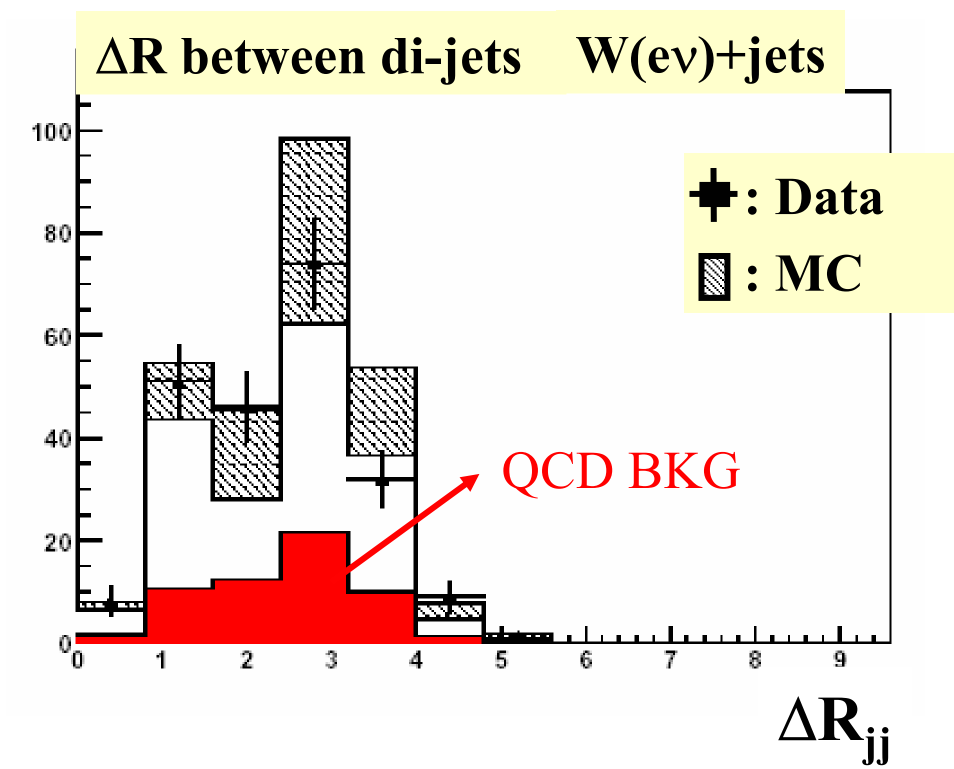
| Single boson | Diboson | Triboson | Heavy flavor |
|---|---|---|---|
| $W+\leq 5j$ | $WW+\leq 5j$ | $WWW+\leq 3j$ | $t\bar{t}+\leq 3j$ |
| $W+b\bar{b}+\leq 3j$ | $WW+b\bar{b}+\leq 3j$ | $WWZ+\leq 3j$ | $t\bar{t}+\gamma+\leq 2j$ |
| $W+c\bar{c}+\leq 3j$ | $WW+c\bar{c}+\leq 3j$ | $W\gamma\gamma+\leq 3j$ | $t\bar{t}+W+\leq 2j$ |
| $Z+\leq 5j$ | $ZZ+\leq 5j$ | $Z\gamma\gamma+\leq 3j$ | $t\bar{t}+Z+\leq 2j$ |
| $Z+b\bar{b}+\leq 3j$ | $ZZ+b\bar{b}+\leq 3j$ | $WZZ+\leq 3j$ | $t\bar{t}+H+\leq 2j$ |
| $Z+c\bar{c}+\leq 3j$ | $ZZ+c\bar{c}+\leq 3j$ | $ZZZ+\leq 3j$ | $t\bar{b}+\leq 2j$ |
| $\gamma+\leq 5j$ | $\gamma\gamma+\leq 5j$ | | $b\bar{b}+\leq 3j$ |
| $\gamma+b\bar{b}+\leq 3j$ | $\gamma\gamma+b\bar{b}+\leq 3j$ | | |
| $\gamma+c\bar{c}+\leq 3j$ | $\gamma\gamma+c\bar{c}+\leq 3j$ | | |
| | $WZ+\leq 5j$ | | |
| | $WZ+b\bar{b}+\leq 3j$ | | |
| | $WZ+c\bar{c}+\leq 3j$ | | |
| | $W\gamma+\leq 3j$ | | |
| | $W\gamma+\leq 3j$ | | |
| | $Z\gamma+\leq 3j$ | | |
| | $Z\gamma+\leq 3j$ | | |

…all at NLO

# W+jets production

- Reconstructed di-jet mass and $\Delta R (= \sqrt{\Delta\phi^2 + \Delta\eta^2})$ between jets
  - MC reproduces jet distributions well
  - First step towards study of $W(\rightarrow \text{leptons})H(\rightarrow bb)$ decay process

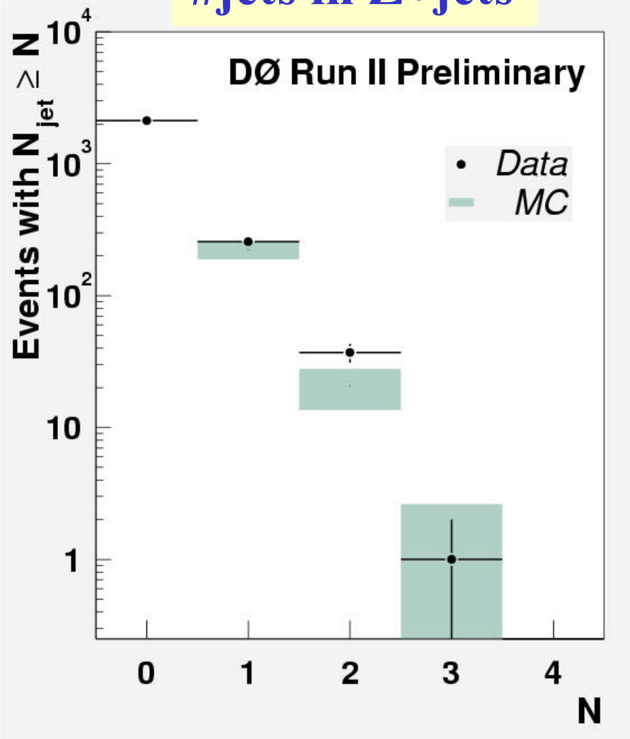


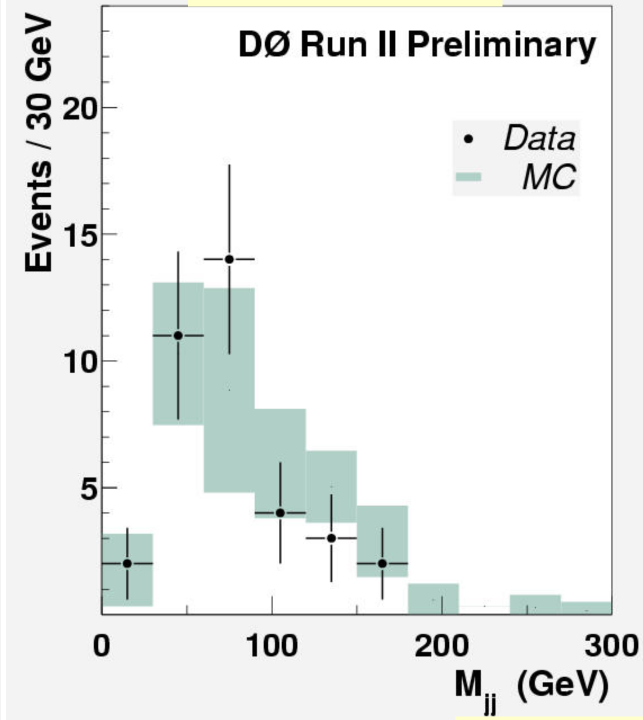
# Z+jets production

- Number of jets in Z + jets final states
- Reconstructed di-jet mass and $\Delta R (= \sqrt{\Delta\phi^2 + \Delta\eta^2})$ between jets
  - MC describes jet distributions well
  - First step towards Z(→leptons)H(→ bb) study

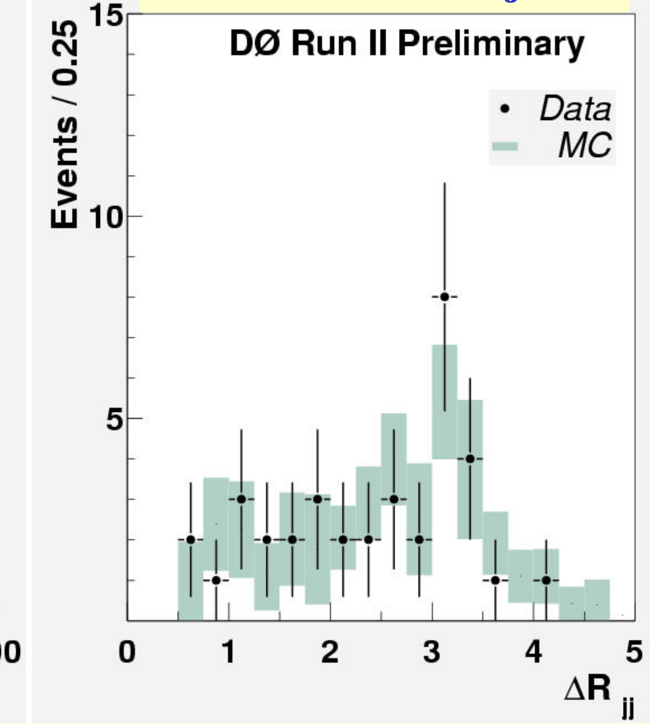
**#jets in Z+jets**




**Di-jet Mass**




**ΔR between di-jets**

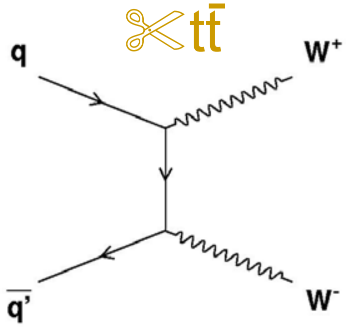


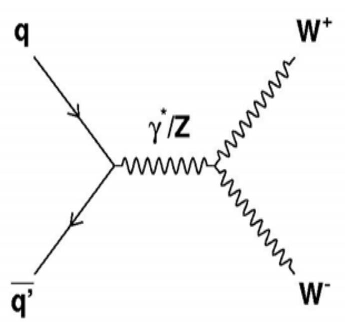

Combined Z(ee)+jets and Z(μμ)+jets

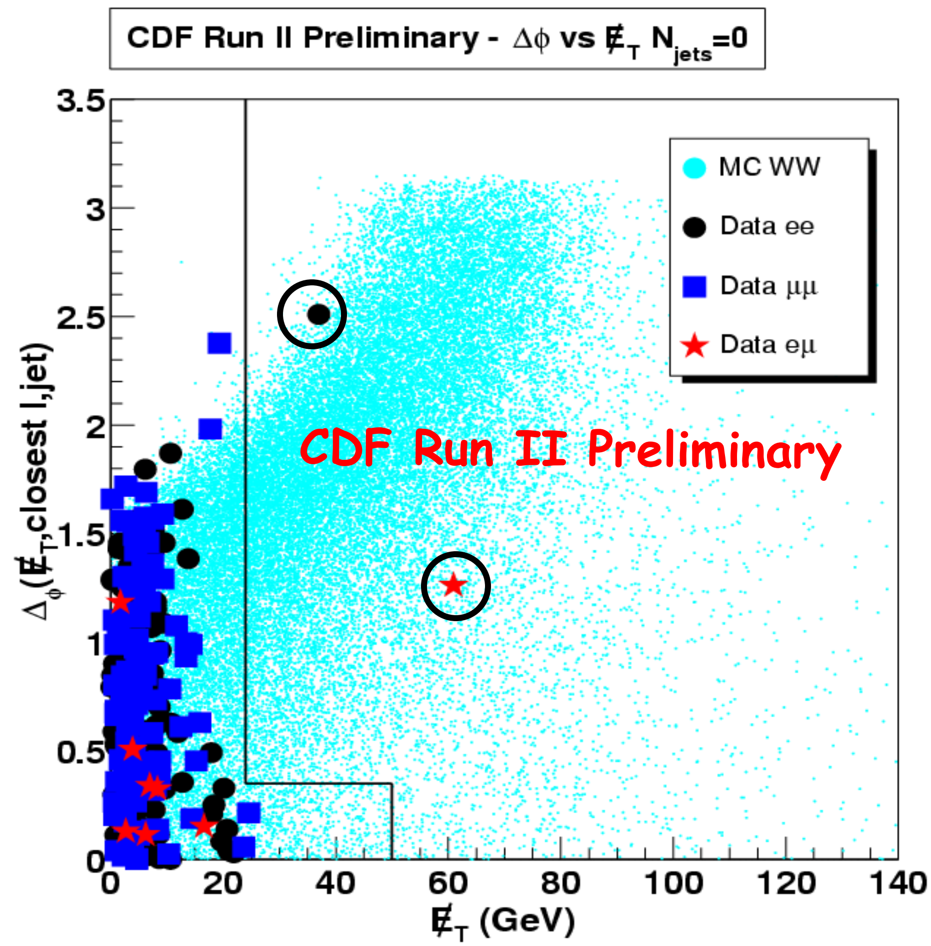
# Dibosons: $WW \rightarrow ll\nu\nu$

Important background for Higgs Search

- Event selection
  - Two isolated high $p_T$ e or $\mu$ with opposite charge
    - ✂ Fakes
  - $\not{E}_T > 25$ GeV
  - $\Delta\phi(\not{E}_T, l/j) > 20^0$ or $\not{E}_T > 50$ GeV
    - ✂ DrellYan, $Z \rightarrow \tau\tau$
  - Z veto
  - Jet veto
    - ✂ $t\bar{t}$



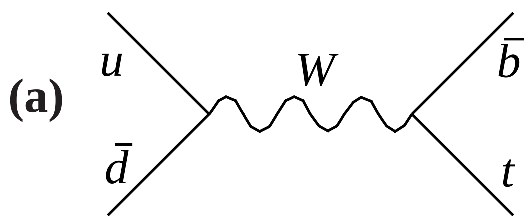




**2 Candidates in ~ 72 $pb^{-1}$**

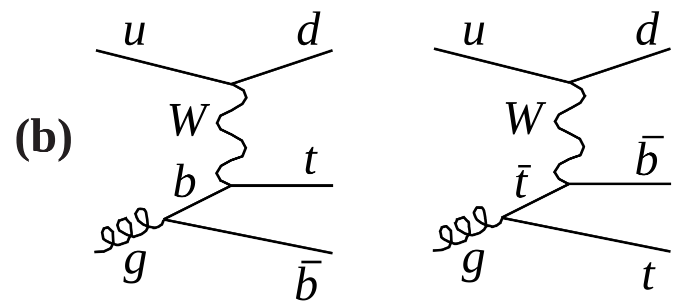
# Single Top: W → tb, g*W → tb

**SM process not yet observed experimentally!**

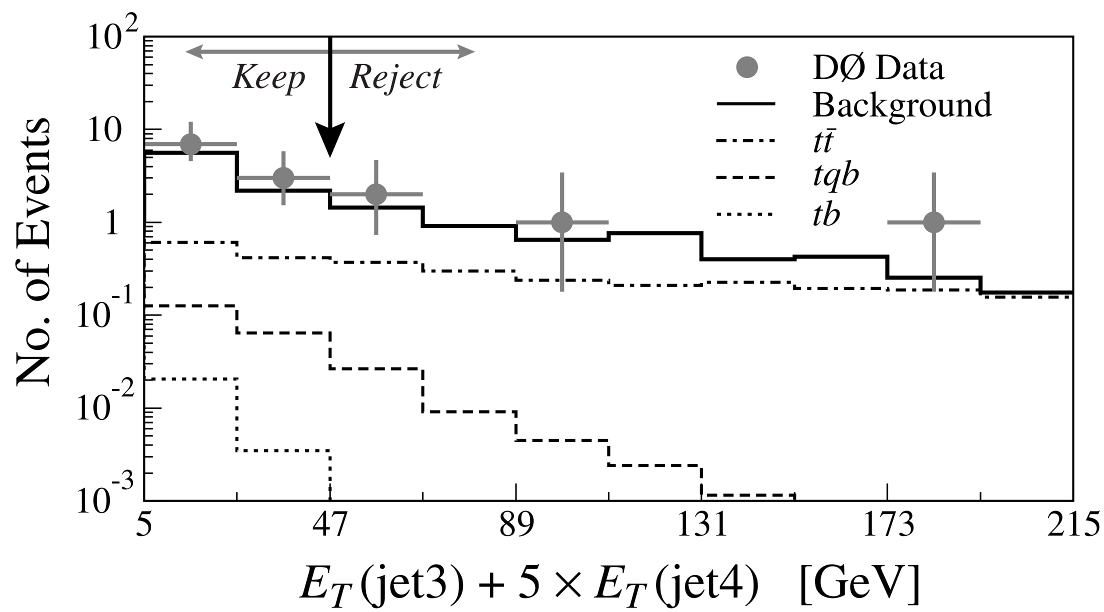
Important background to W/Z H




(a) s-channel annihilation




(b) t-channel W-gluon fusion




Run 1

# Tevatron Higgs Sensitivity Study (2003)

## The Stage is Set...

- The DoE requested a new estimate for Higgs search sensitivity in Run II
  - Job to be shared by CDF & D∅
- Split the task between collaborations
  - **CDF – WH→lνbb**, **D∅ – ZH→ννbb**
- Very short timescale: ~5 months
  - No time to do a full analysis
  - Must work very hard, very fast

# What *else* changed since 1998?

## Things that *help*:

- Full simulation of Run II detectors (GEANT)
- Real measurements of trigger rates and efficiencies
- Greater understanding of physics processes
- Lots of data to make comparisons with
- More sophisticated analysis techniques

## Things that *don't help*:

- Changes in expected cross sections
- Tevatron bunch crossing time will not be 132ns
  - larger rate of multiple interactions

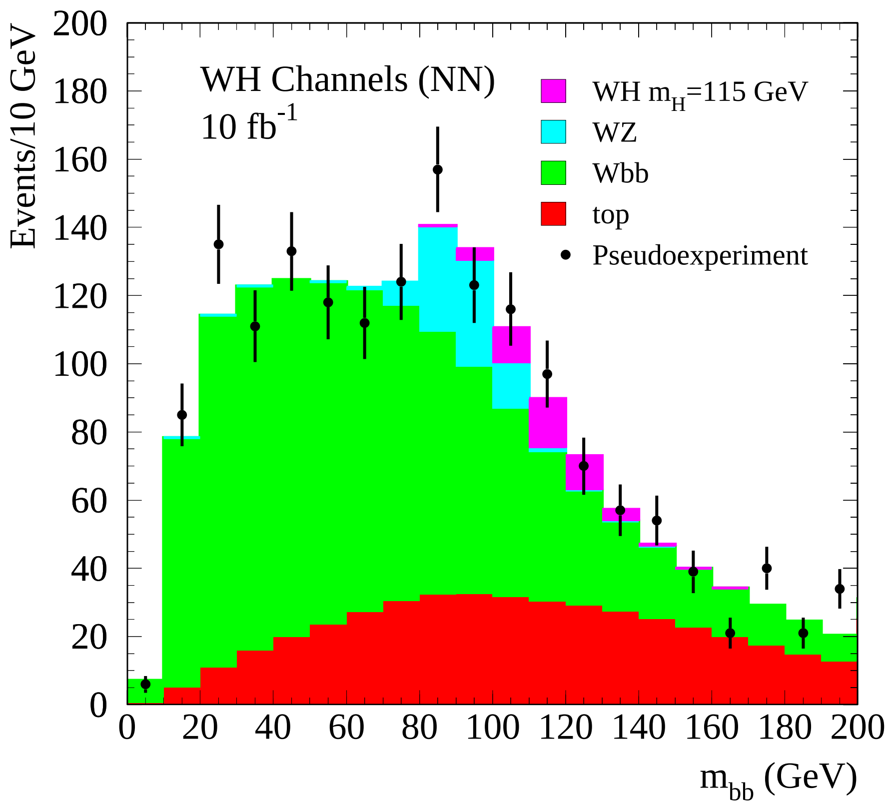
**Select Cross Sections (pb)**

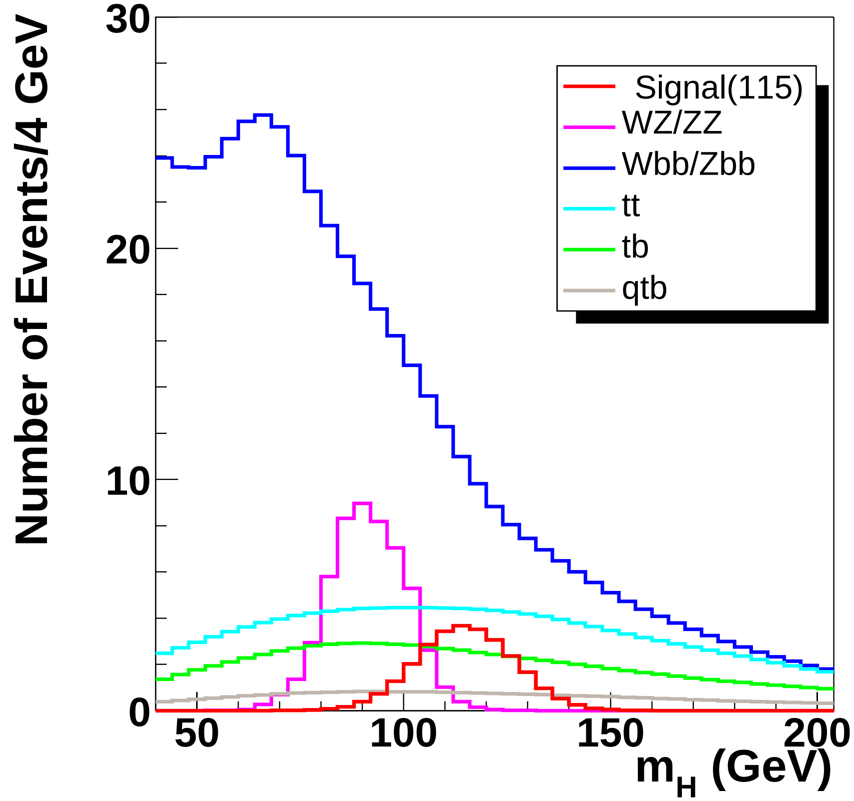
| | New | SHWG | Ratio |
|---|---|---|---|
| $ZH(\nu\nu)$ $m_H$=120 GeV | 0.013 | 0.016 | 0.79 |
| Wbb | 3.40 | 2.53 | 1.34 |
| WZ | 3.20 | 2.81 | 1.14 |
| ZZ | 1.70 | 1.24 | 1.38 |

# Signal and background: WH→lνbb (CDF)

$M_H$ = 115 GeV

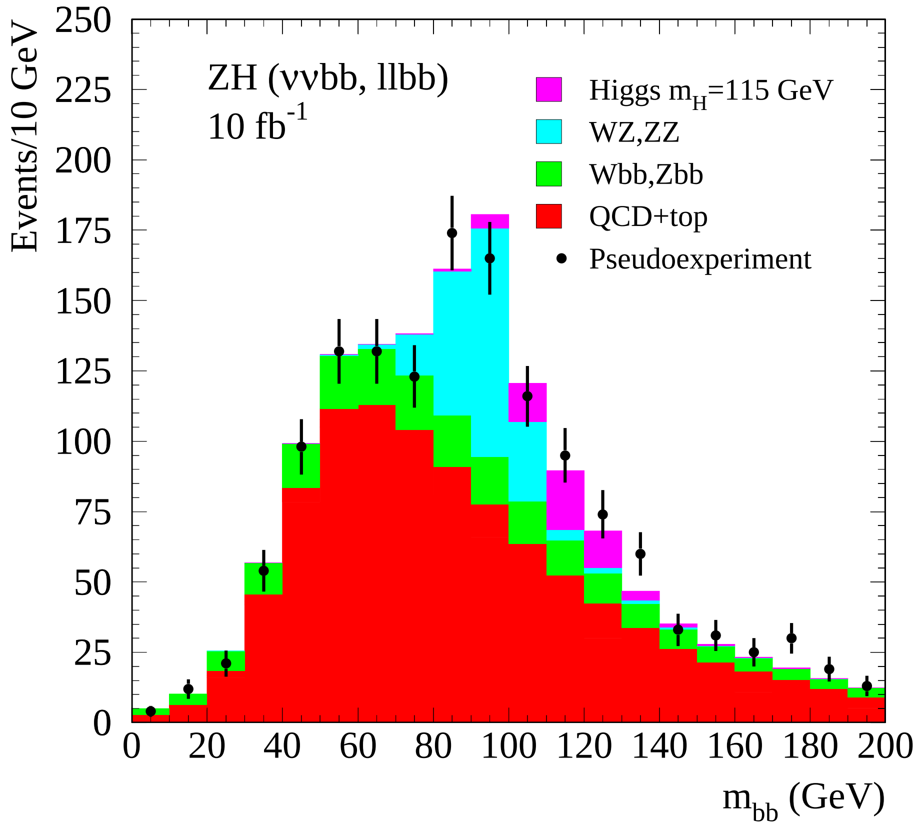
(10 inv fb, single expt.)

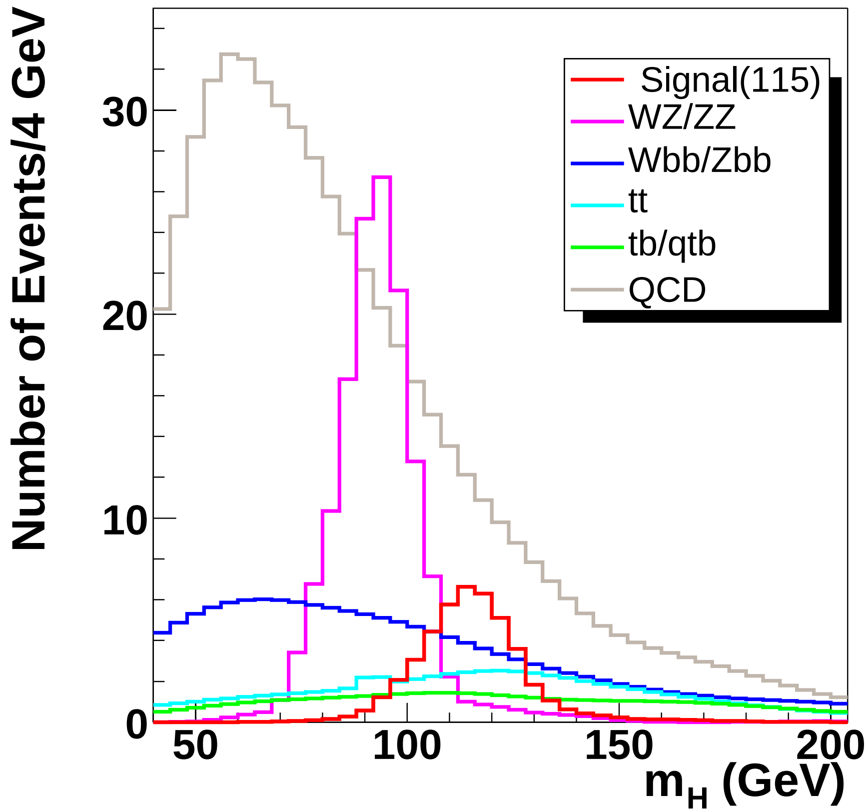


# Signal and background: ZH→ννbb (D0)

$M_H$ = 115 GeV
(10 inv fb, single expt.)




ZH→llbb contribution added by scaling ZH→ννbb by 1.33

# CDF/D0 combination results

- Many believed the SHW study (1999) was over optimistic!
- Complete studies of realistic detector performance place results on firmer ground
  - b-tagging, trigger, di-jet mass resolution, QCD background
- HSS exceed the expectations of SHW!
- Should get better (new ideas, optimisation, lots of time, smart people)
- But, Run IIB silicon upgrade cancellation is big setback (double b-tag eff. reduced)

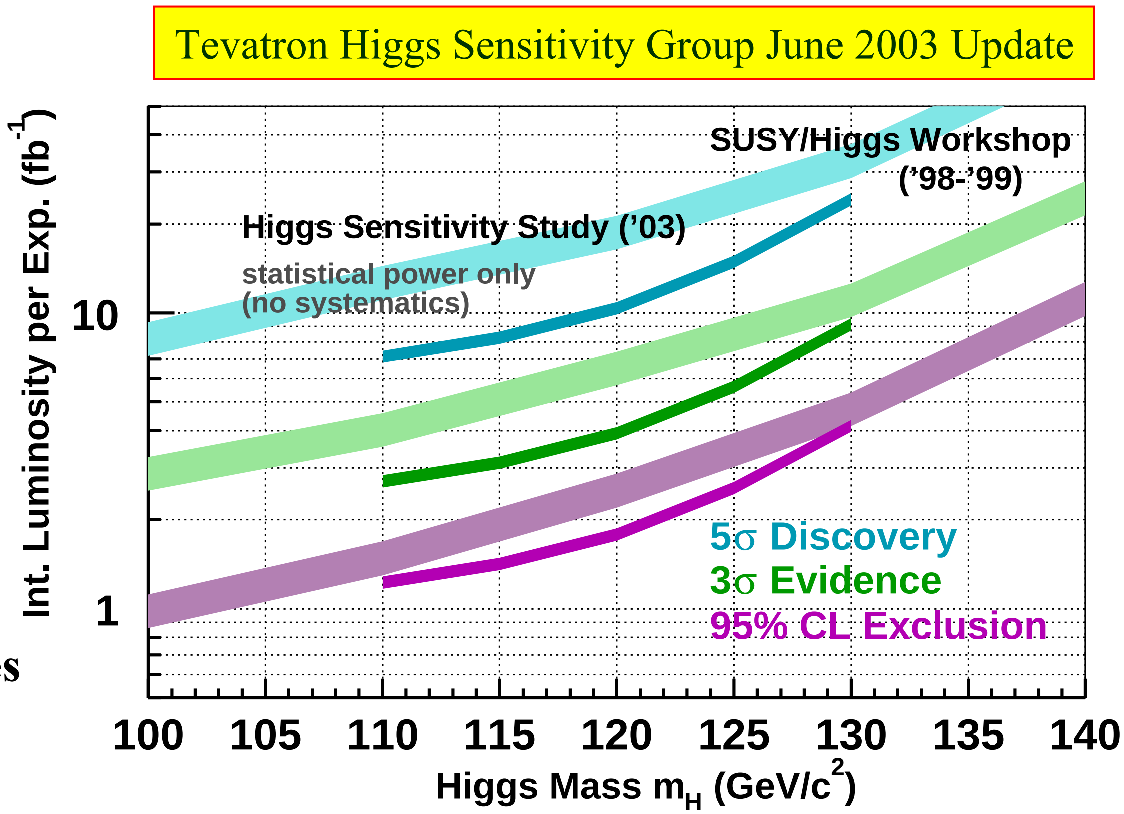
**Assumes 10% dijet mass resolution**

**Uses Run IIB Silicon (Beware!)**

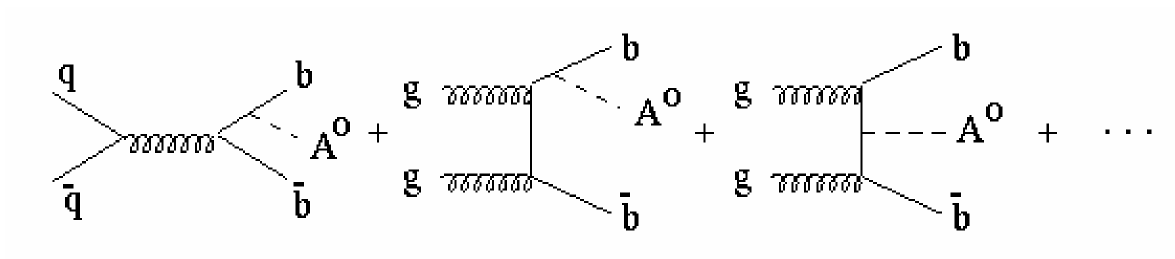
**Width of HSS bands determined by method uncertainty**

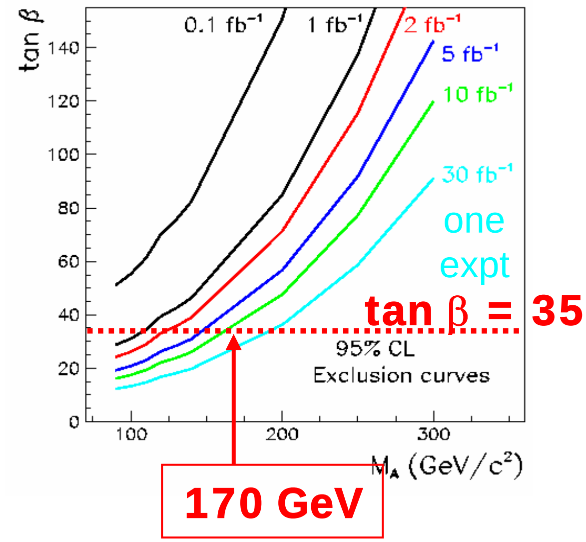
**Width of SHW bands given by 30% uncertainty**

**SHW included H → WW (contributes at high $M_H$)**



# Tevatron: SUSY Higgs potential?

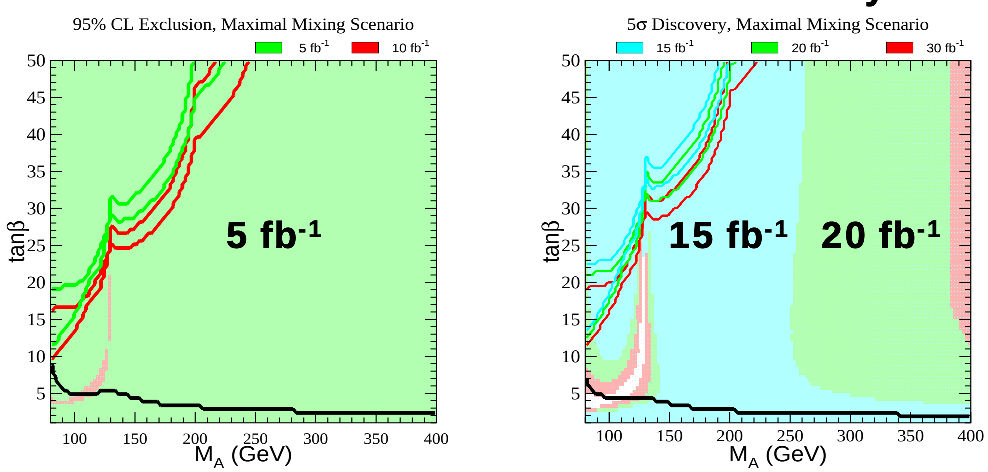



$\sigma \sim 1$ pb for $\tan\beta = 30$
and $m_h = 130$ GeV

**bb(h/A) → 4b**

**95% exclusion** | **5σ discovery**

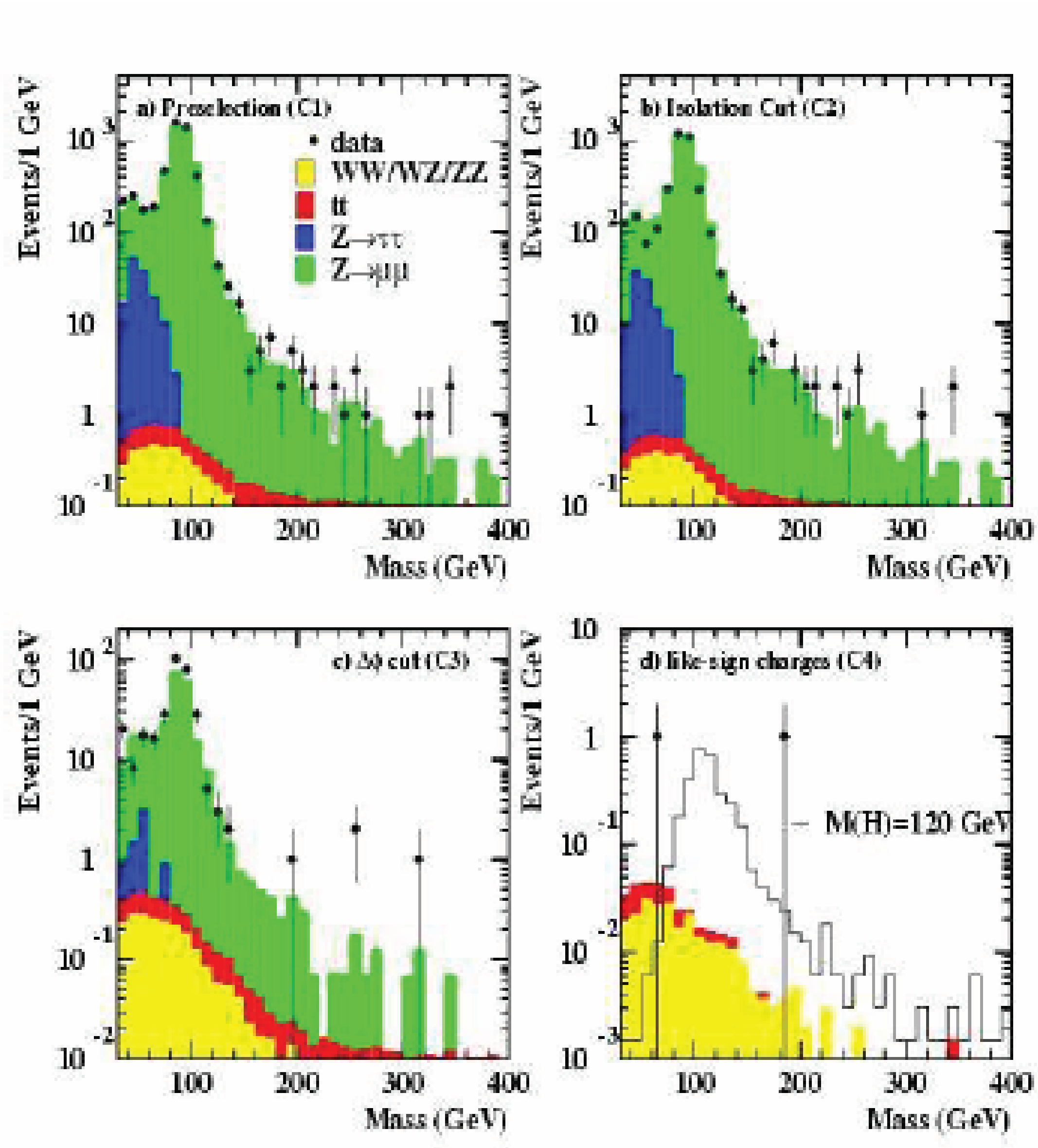



**Luminosity per experiment, CDF + DØ combined**

**Exclusion and discovery for maximal stop mixing, sparticle masses = 1 TeV**

old estimates
- need updating!

# Doubly-Charged Higgs Bosons




D-Zero Run II (preliminary)

**LR symmetric & Triplet Models**

**decays into like-sign di-leptons**

**only muons considered**

**mass limit of 116 GeV is better than OPAL limit of 100.5 GeV**

**results presented at summer conferences**

# Future Machines

- LHC
- Linear Collider

On the 'road map'

- Muon Collider ($\sigma_H = 4 \times 10^4\, \sigma_H^{LC}$ !!!)
- VLHC
- ??

Speculative

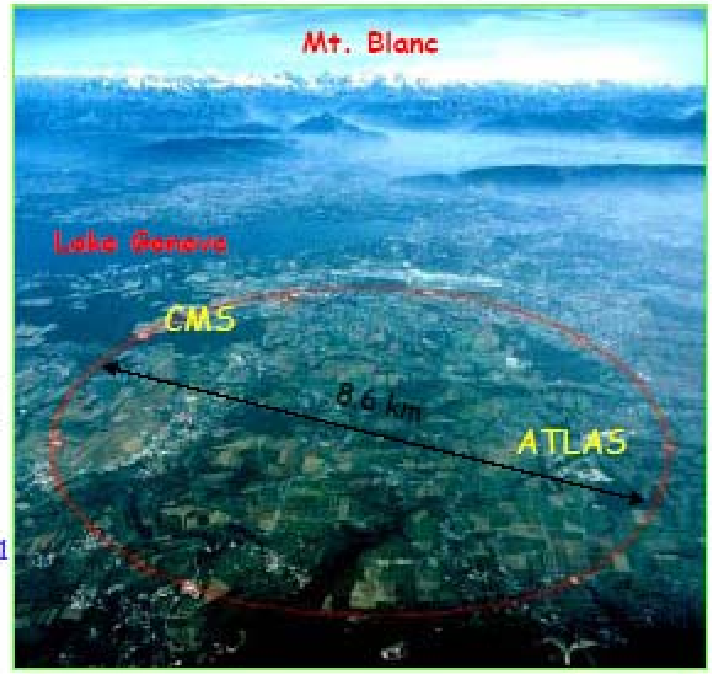
# The experiments: The LHC at CERN

The Large Hadron Collider (LHC) at CERN will collide protons with protons at 14 TeV. This will provide collisions of the constituent quarks and gluons to about 5 TeV.

General purpose experiments ATLAS and CMS.

First collisions are expected in 2007; first physics run in 2008 and first results in 2009??

Luminosity should reach $1 \times 10^{34}\ cm^{-2}\ s^{-1}$




The LHC will reach the energy scale where current experiments tell us that new physics should surely exist

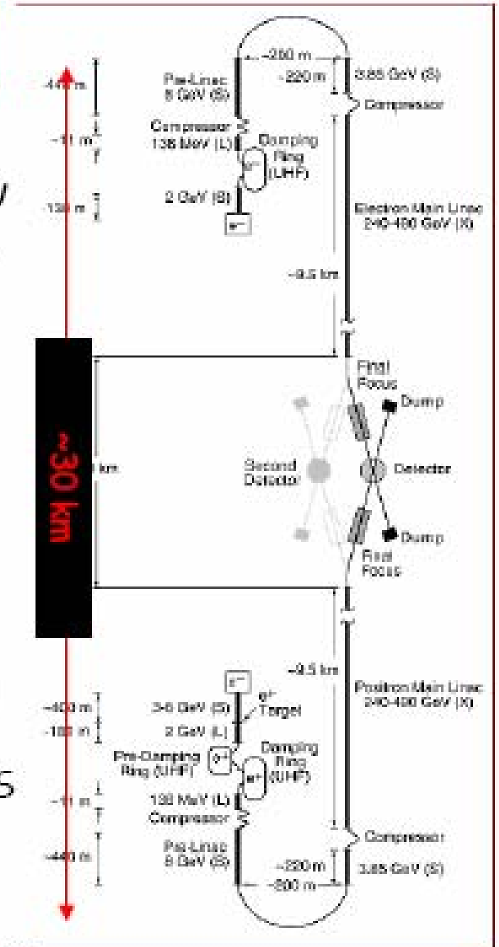
# The $e^+e^-$ Linear Collider (proposed)

The first phase of the LC should collide $e^+$ and $e^-$ at energies up to 500 GeV. Luminosity up to a few x $10^{34}$ $cm^{-2}$ $s^{-1}$. Electrons polarized to above 80%.

First operation in 2015 ???

Upgrades and options:

- energy increase to about 1 TeV
- Polarized $\gamma\gamma$ collisions (backscattered laser light); also $e^-\gamma$ and $e^-e^-$ collisions)
- Polarized positrons




Two technology proposals exist - the TESLA proposal (Germany) using superconducting rf cavities, and the room temperature rf proposals of Japan (JLC) and US (NLC).

Expensive (~$5B)!

R&D continues on 5 TeV linear collider (CLIC at CERN).

# The synergy of the 3 machines

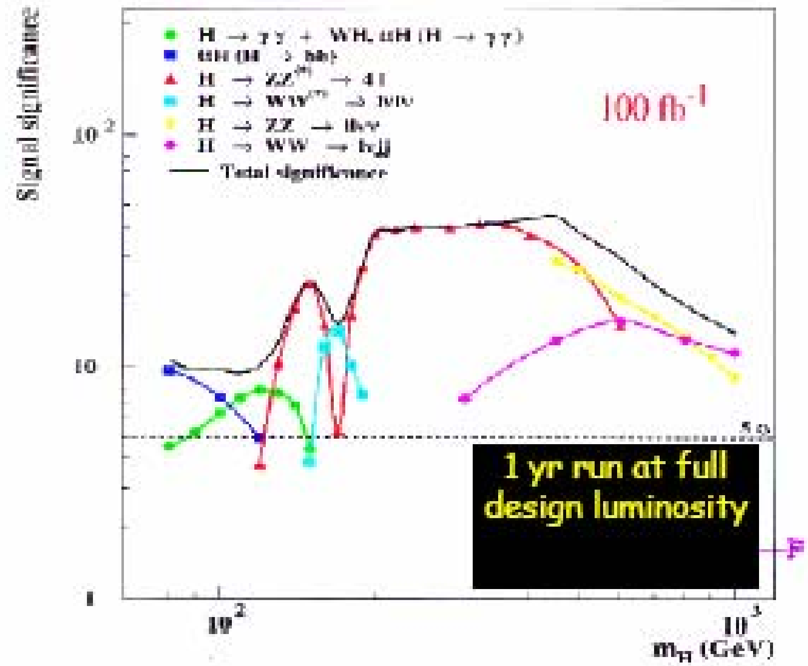
**Tevatron**: operating now with seasoned detector collaborations. Energy is limited however and will access only a part of the terra incognito where new physics can lurk. We need to complete this program and discover what we can.

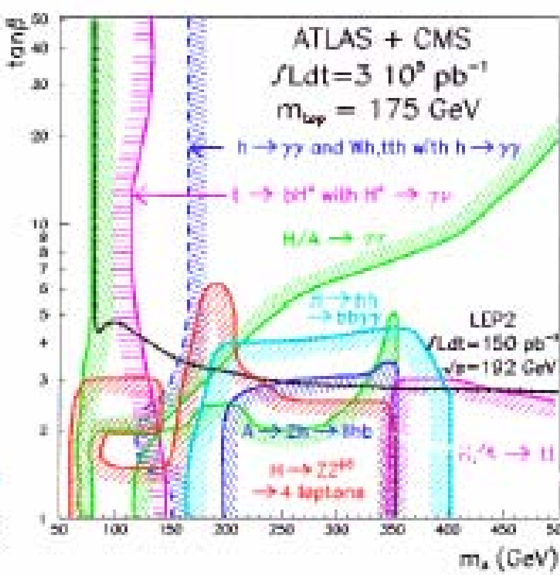
**LHC**: being built and fully funded, has the largest energy reach so should span the TeV scale new physics regime. The colliding quarks and gluons within the protons have a range of energies, and the initial state quantum numbers are not fixed. The collision rates are very high (Giga Hz) and the backgrounds from SM and new physics processes are large; experiments are challenging.

**LC**: 500 GeV energy is large enough to explore the EW symmetry breaking (Higgs) physics and some part of the new physics (SUSY etc.), but not all. However, the initial state has a fixed cm energy and well-defined quantum state. The processes are simple, and rates and backgrounds are low. The LC will provide the detailed and precise information to sort out the new physics.

## Higgs boson and EW symmetry breaking

**LHC** will be able to discover SM-like Higgs boson (> 5σ) from the current limit up to 1000 GeV. Low mass region favored in SM is hardest; only $H \rightarrow \gamma\gamma$ observed. Determine Higgs mass to fraction of %. Can measure width if $M_H$ > 200 GeV. Determine the ratio of branching fractions of Higgs for some decay channels to ~25%.



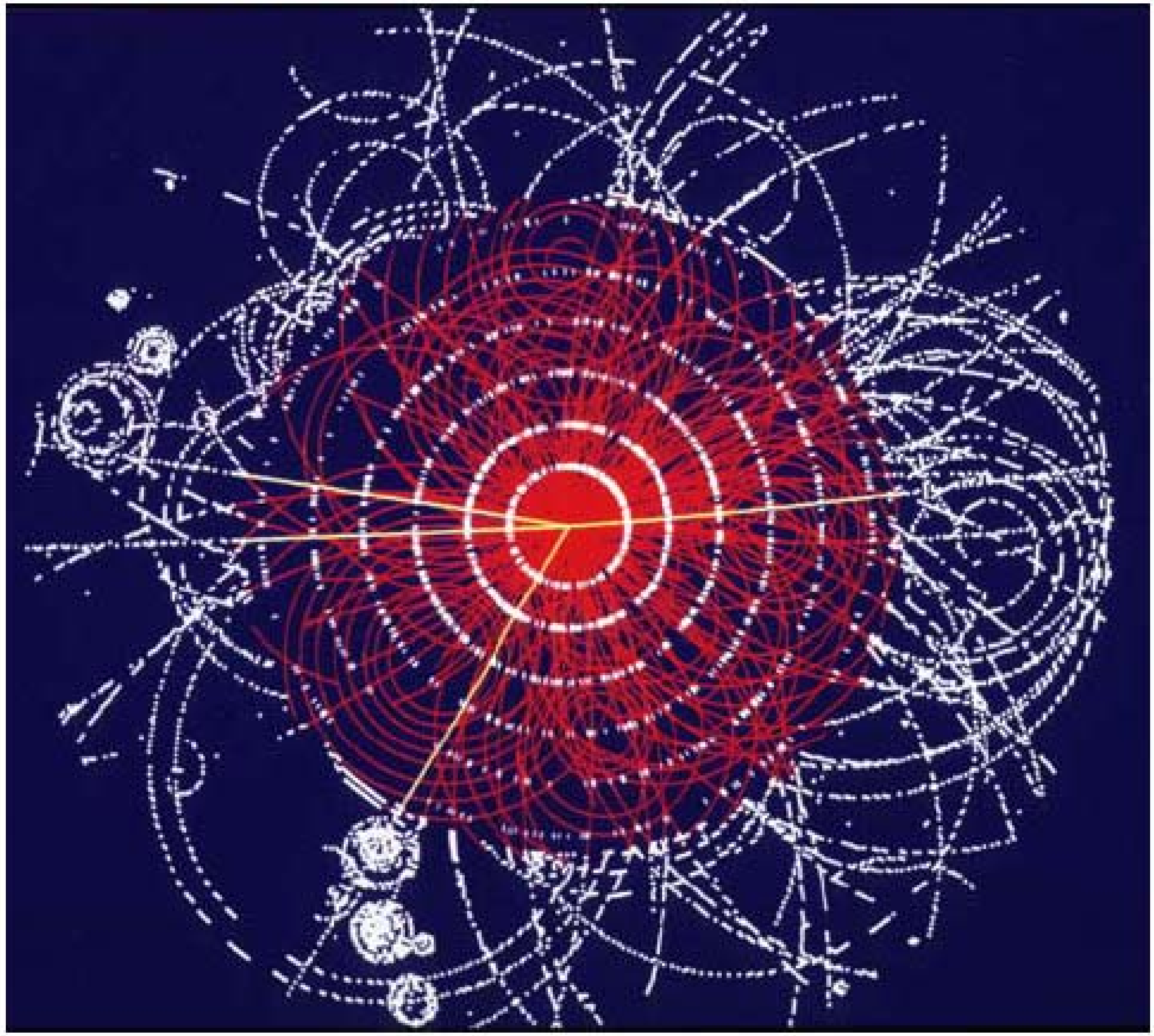




Susy Higgs states: can always observe at least 1, typically 2 or more, but require several years at full luminosity.

# Higgs at ATLAS

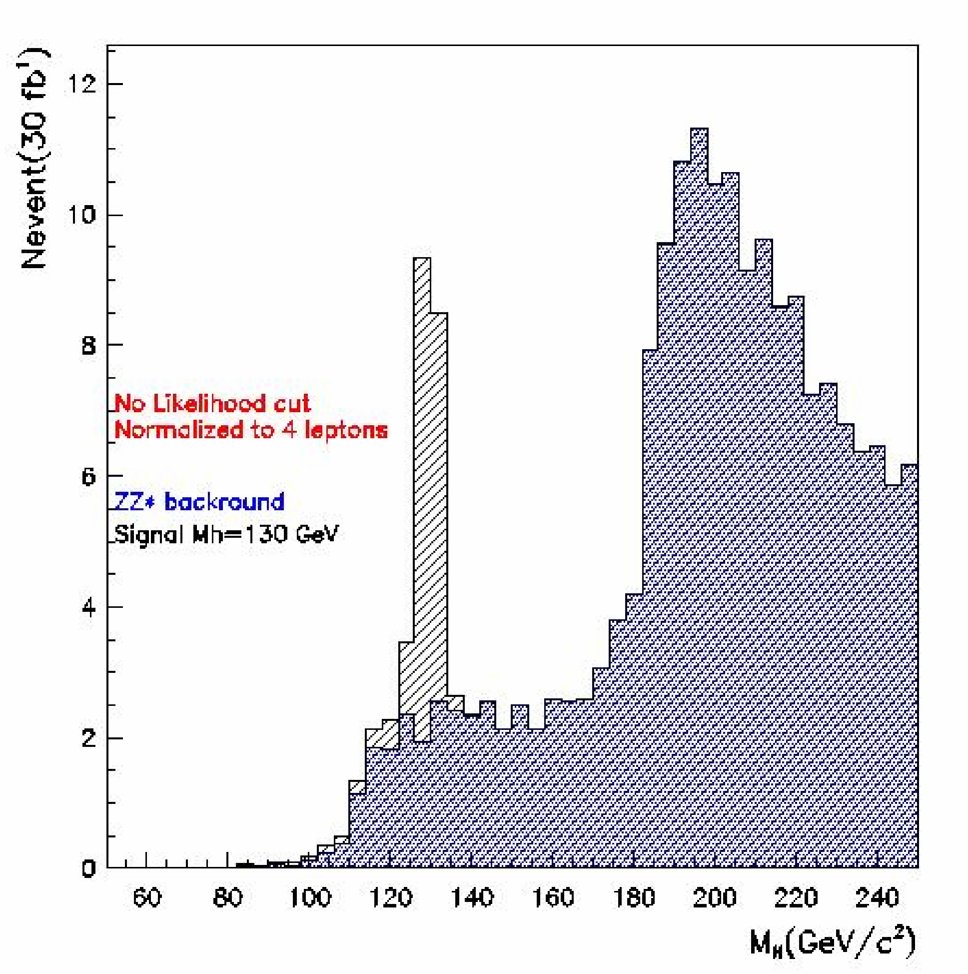
$H \rightarrow ZZ$

$\rightarrow \mu\mu\mu\mu$



# ATLAS $H^0 \rightarrow$ 4 charged leptons

$M_h$=130 GeV Athena 6.6.0



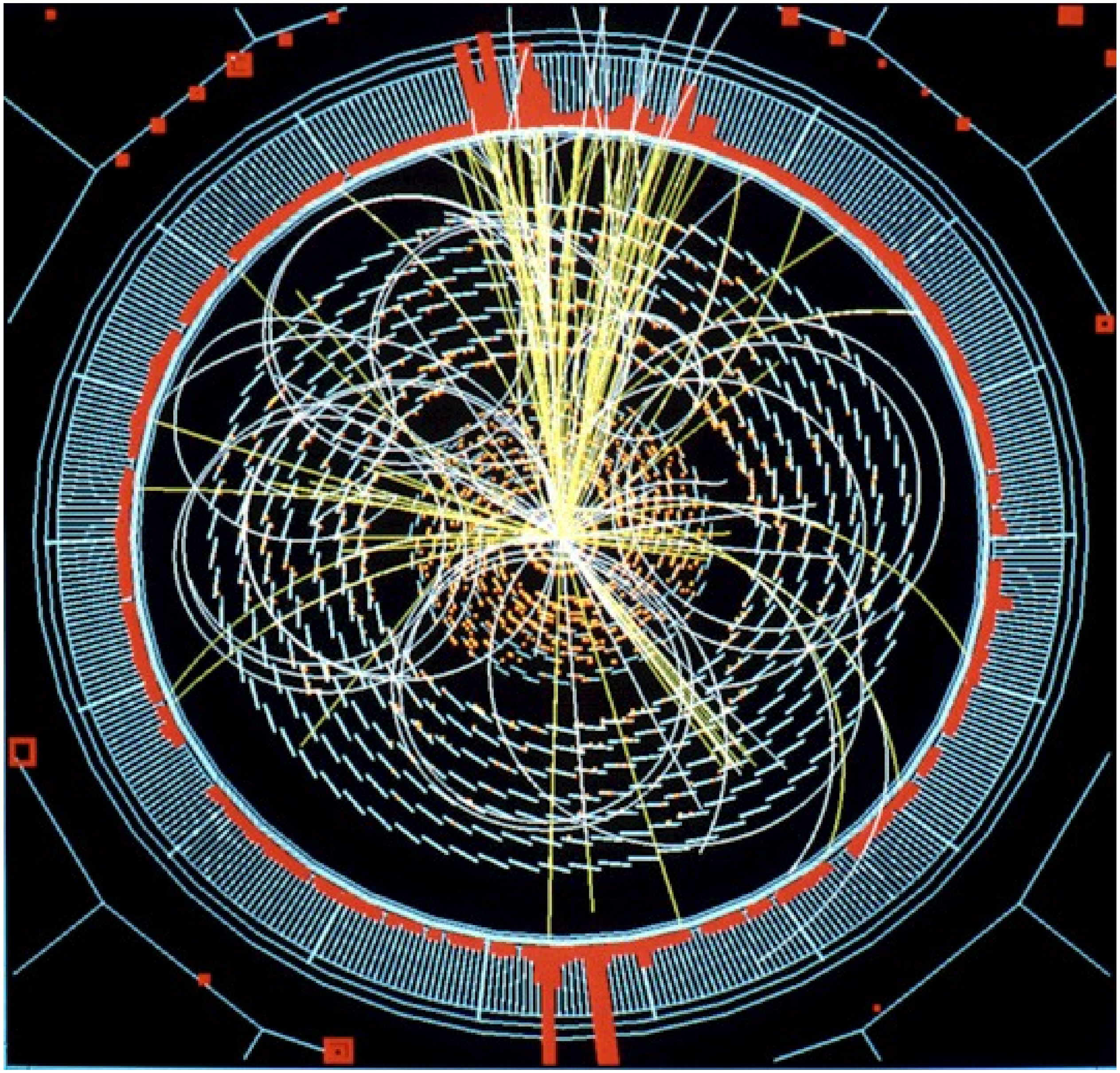

Same mass resolution for ee, emu and mumu assumed

Low-Luminosity setup

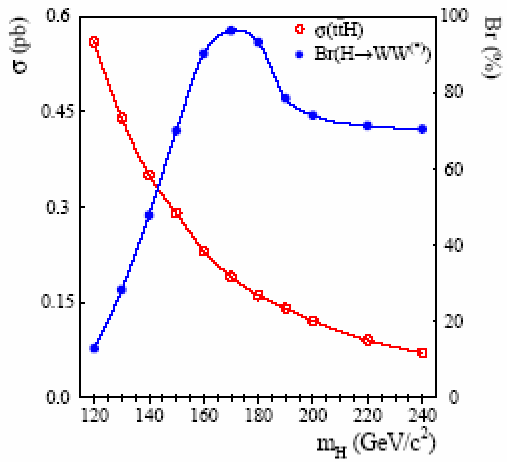
# Higgs at CMS

H→ZZ

→eeqq

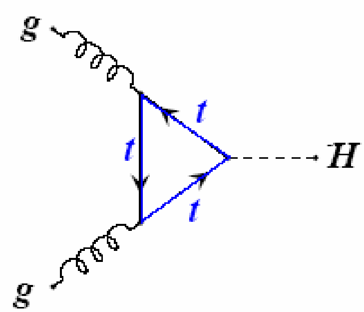


# ttH Production




⇒ Comparison with the indirect measurement

gg → H (top quark loop)




allows to probe additional contribution from SUSY, 4th heavy fermion family...

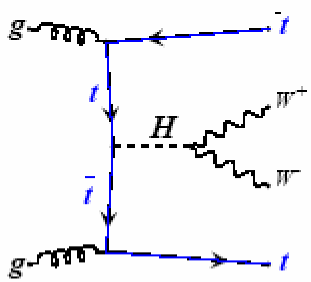
Direct determination of

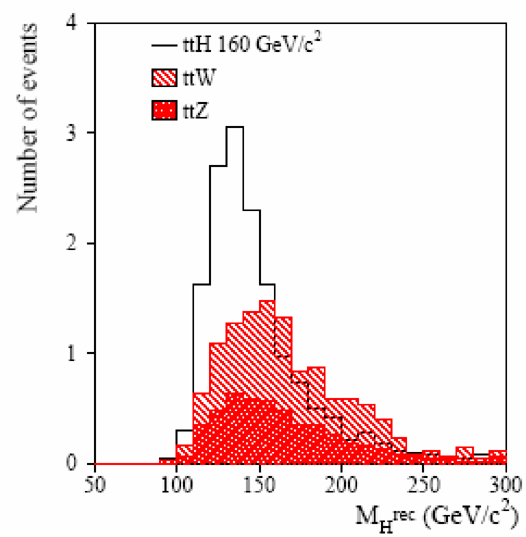
Top quark Yukawa

Coupling $\lambda_t$

in the mass range

[130-200] GeV/$c^2$

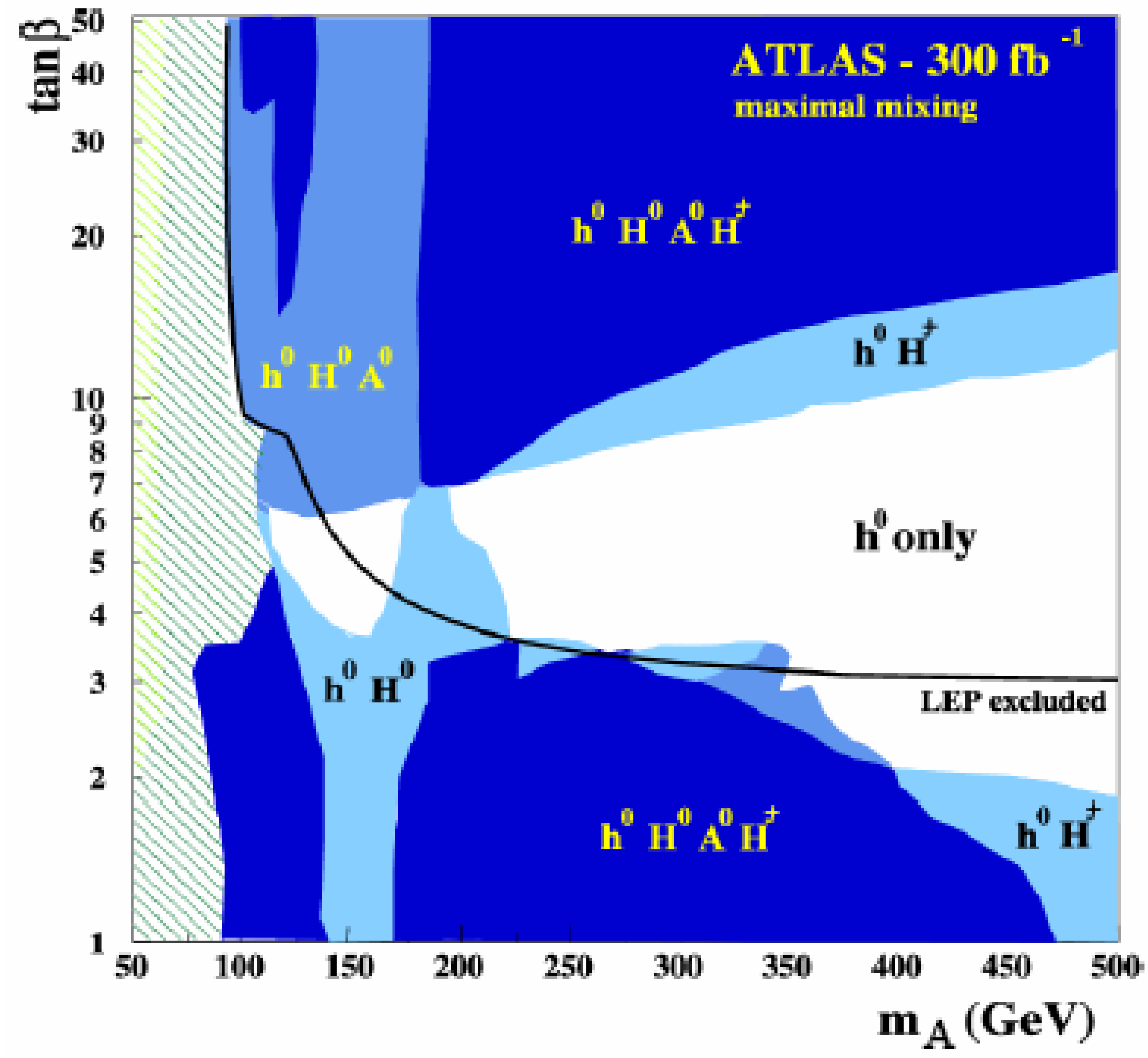



ATLAS
30 fb$^{-1}$

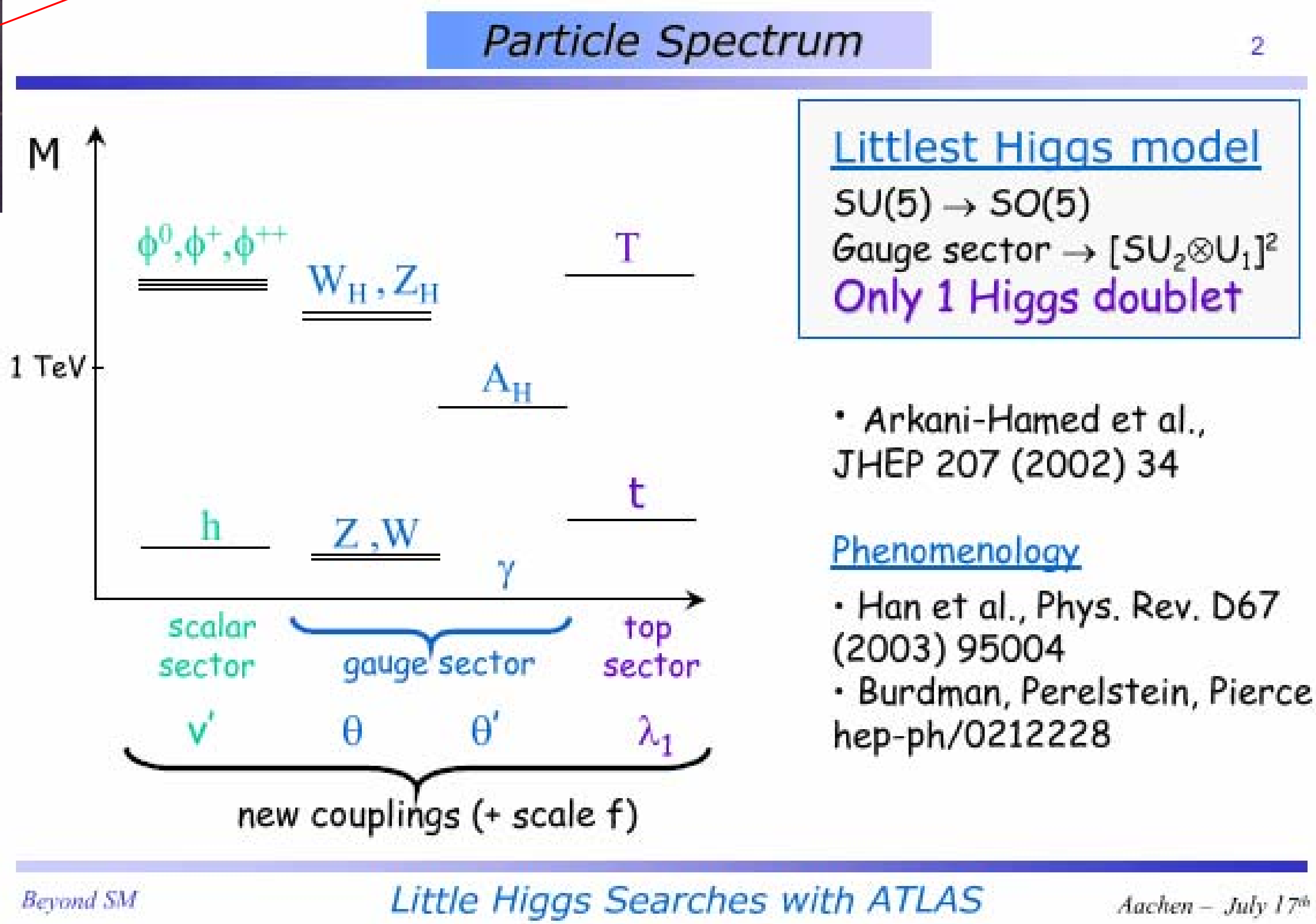
Results : S/B $\geq$ 1 @ $m_H$= 160 GeV/$c^2$

# MSSM Higgs Scenarios at the LHC



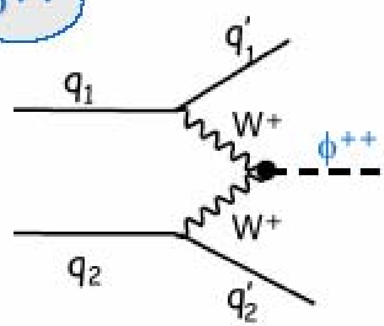
# Little Higgs Model


Peter Higgs
+ grandchild



# Strategies at LHC

## $\phi^{++}$




**VBF mechanism**

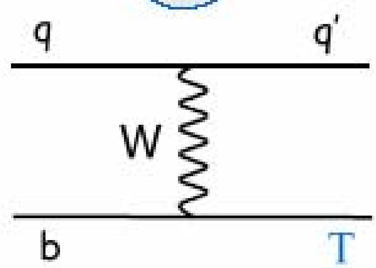
$\sigma \sim (v')^2$

$v'$ should be small

$\phi^{++} \rightarrow W^+W^+$

large SM bkg

## T



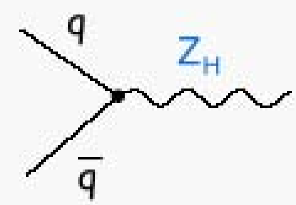

**Wb fusion**

$\sigma \sim (\lambda_1)^2$

$\lambda_1 \sim 1$ but suppressed by *b*-quark PDF.

$T \rightarrow bW, tZ$ — clear signal

## $Z_H$




**$q\bar{q}$ annihilation**

$\sigma \sim (\cot\theta)^2$

Wide range in $\cot\theta$ possible.

$Z_H \rightarrow e^+e^-$ — clear signal

# Search for $Z_H$

$q\bar{q} \longrightarrow Z_H \longrightarrow e^+e^-$

$\mu^+\mu^-$ *not used due to invariant mass resolution*

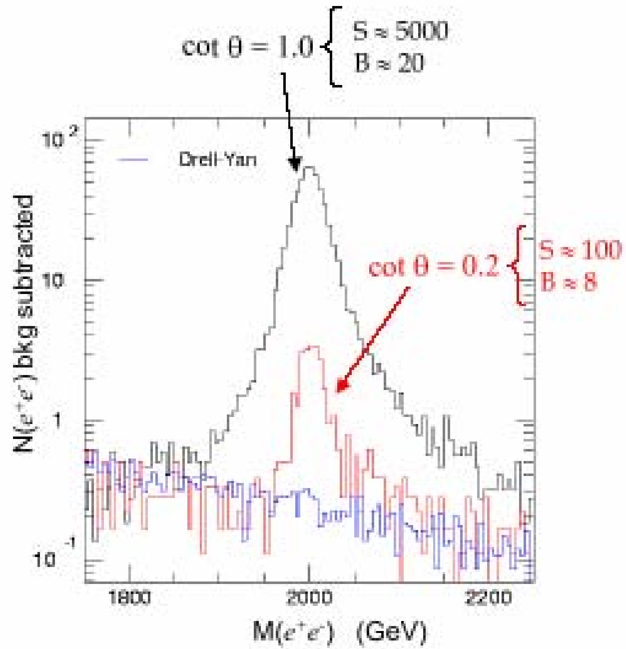
Selection cuts:

- 2 isolated electrons with $p_T > 20$ GeV and $|\eta| < 2.5$
- minimum invariant mass equal to 800 GeV

Background:

Drell-Yan ($q\bar{q} \rightarrow Z/\gamma \rightarrow e^+e^-$)
other bkg's are under evaluation

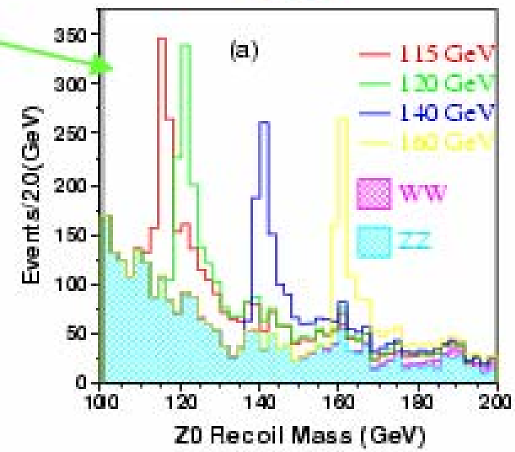
$M(Z_H) = 2$ TeV $\quad \mathcal{L} = 3\cdot10^5$ pb$^{-1}$

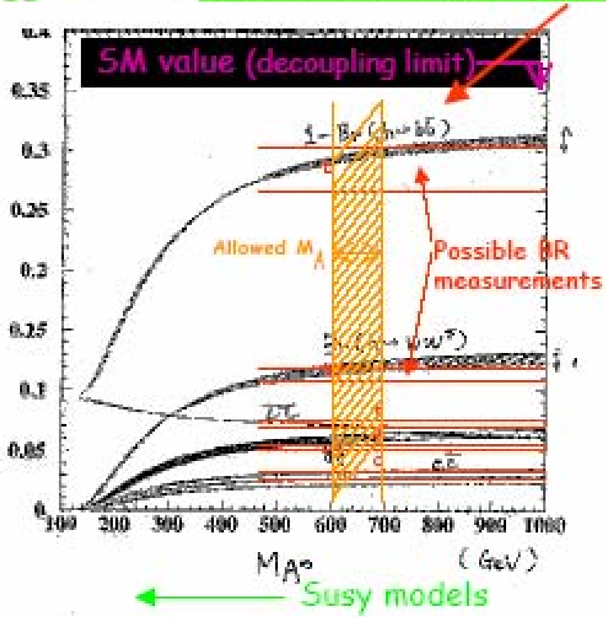


# Higgs boson and EW symmetry breaking

**LC** produces Higgs from $e^+e^- \rightarrow ZH$ or $H\nu\nu$.
Seeing Higgs recoil from Z gives 'bias free' Higgs laboratory in which one can *measure* Higgs branching ratios ($b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, $gg$, $W^+W^-$) to a few %.
These BRs are crucial for establishing whether the Higgs seen is <u>SM, Susy or other model.</u>

Higgs of several possible mass values seen as recoil to Z




The LC will establish the spin-parity of the Higgs state and its width; measure the ttH coupling; measure the Higgs self-coupling $g_{HHH}$ which is related to the shape of the Higgs potential and to the Higgs mass, thus is a crucial constraint on the model.

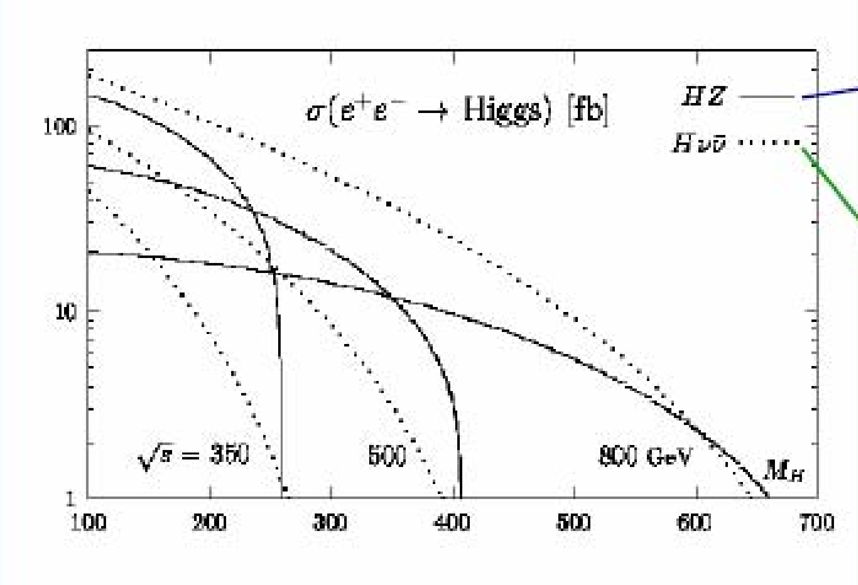


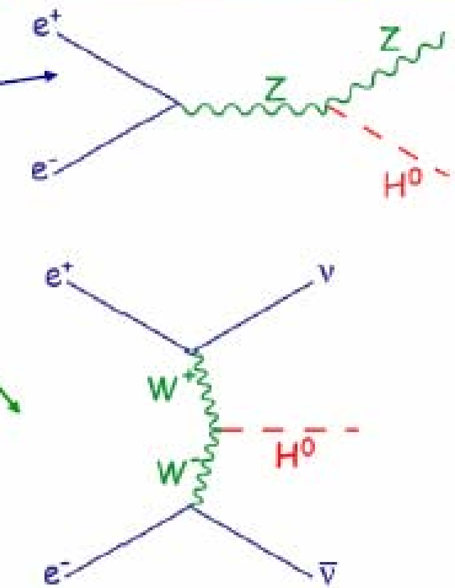
**Tevatron or LHC discover the Higgs: LC tells us what it really is**

# A Linear Collider as a Higgs Boson Analyzer

- Measure the Higgs properties:
  - Production rate
  - Mass
  - Spin & Parity
  - Lifetime
- Branching Fractions (Couplings to)
  - Matter particles: $g_{hff}$
  - Gauge bosons: $g_{hZZ}$
- Establis the Higgs mechanism as the mechanism of electroweak Symmetry Breaking by measuring the Higgs coupling to itself : $\lambda$
- Due to its intrinsic limitations ($E_{CM}$, ee nature) some unique properties can be better probed by a $\gamma\gamma$ collider (H$\gamma\gamma$ coupling, Beyond the SM Heavy Higgs Bosons ) and a Multi-TeV LC (CLIC) (Rare Higgs Decays…)

# Higgs Production at a LC (The Gold…)



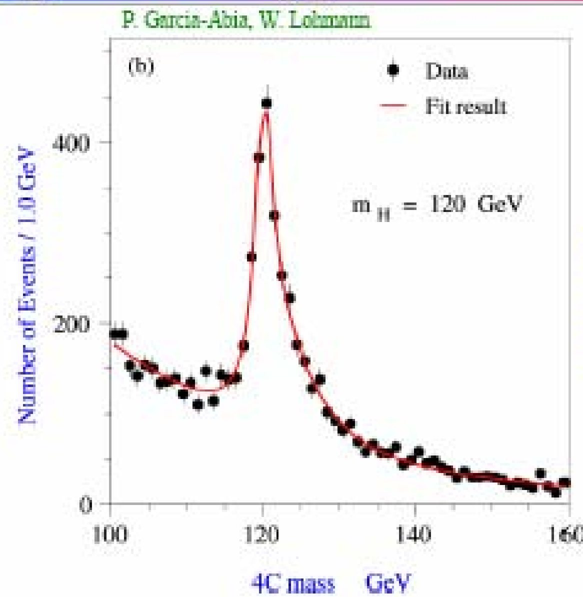



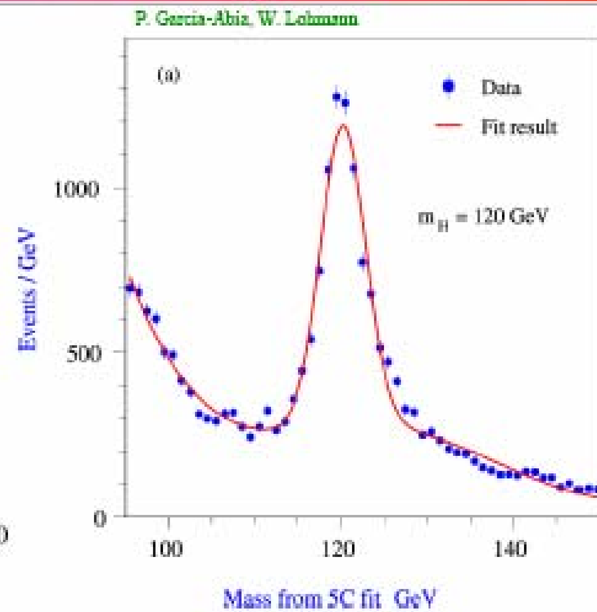

- Production cross section is >100 fb for a 120 GeV Higgs boson
- Each 10 $fb^{-1}$ will deliver >1000 120 GeV Higgs bosons !!!!

A Linear Collider is a GOLD mine for Higgs Bosons and there is not much DROSS (bg) around

# Measuring the Higgs Boson Mass $m_H$<130 GeV

- Exclusive final states analyses allow high accuracies on Higgs mass measurements

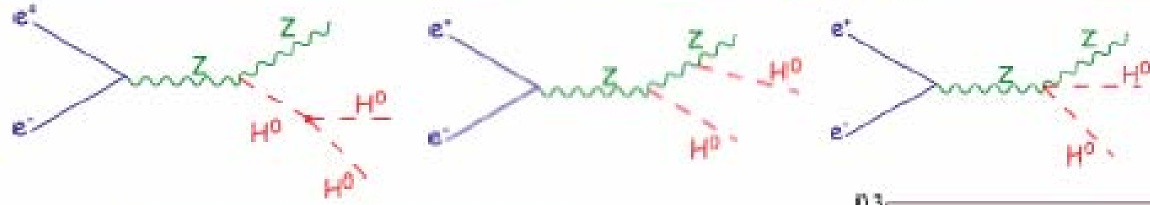

- ee→HZ →qqll signature: 2 isolated leptons recoiling against 2 jets, use 4C fit (energy momentum conservation) Mass is obtained via a fit of Signal on top of BG

- ee→HZ →bbqq signature: 2 b-tagged jets recoiling against 2 jets, use 5C fit (energy momentum conservation+$m_Z$ constraint on 2 jets) Mass is obtained via a fit of Signal on top of BG

| $m_H$ | llqq | qqbb | Combined |
|---|---|---|---|
| 120 GeV | 70 MeV | 45 MeV | 40 MeV |

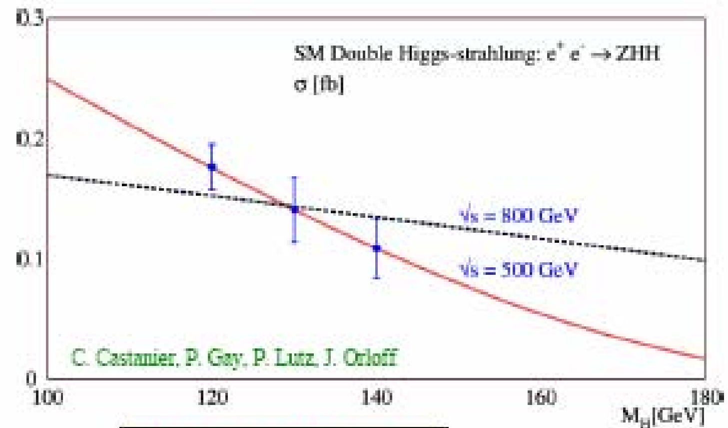
(500/fb@350)

# Probing the Higgs Potential




$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

- Cross section for double Higgs production is very low: $\sigma(ee \rightarrow HHZ)$~0.15-0.2 fb for 120 GeV Higgs @ $E_{CM}$=800-500 GeV
- Signature: 4 b-tagged jets+Z boson Large 4 and 6 fermion BG
- Need to extract coupling from total cross section!
- Need very high luminosity to be sensitive ($1000\ fb^{-1}$ @ $E_{CM}$=500 GeV)




(1000/fb@500 GeV)

| $m_H$ (GeV) | 120 | 130 | 140 |
|---|---|---|---|
| $\delta\sigma/\sigma$ | 18% | 14% | 11% |

$\Delta\sigma/\sigma$=14 % leads to $\Delta\lambda_{HHH}/\lambda_{HHH}$=24 % ("dilution effect")
(for 1 $ab^{-1}$ @ 500 GeV)

# Hfitter - A Global Higgs Fitter

- Use the HDECAY program to build a Higgs fitter

K. Desch, M. Battaglia

(500/fb@500 GeV)

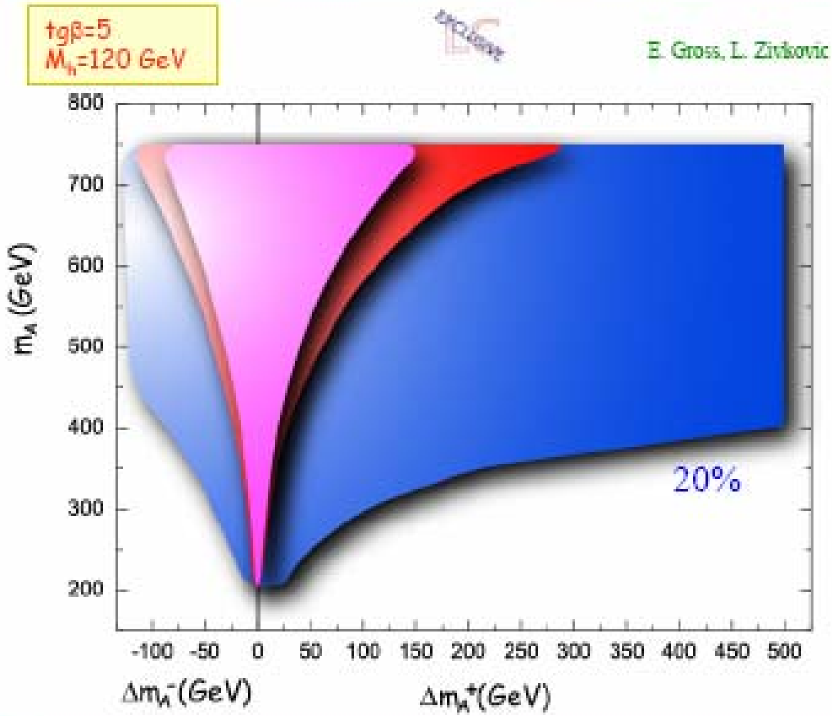
| Measurement | Relative Error | Sensitivity to |
|---|---|---|
| BR(H →bb) | 2.4% | $g_{Hbb}$ |
| BR(H →cc) | 8.3% | $g_{Hcc}$ |
| BR(H →ττ) | 5% | $g_{H\tau\tau}$ |
| BR(H →gg) | 5.5% | $g_{Hgg}$, $g_{Htt}$ |
| BR(H →WW) | 5.1% | $g_{HWW}$ |
| BR(H →γγ) | 26% | $g_{Htt}$ |
| σ(ee →HZ) | 2.5% | $g_{HZZ}$ |
| σ(ee →Hνν) | 2.8% | $g_{Hbb}$ ,$g_{HWW}$ |
| σ(ee →ttH) | 11% | $g_{Htt}$ |

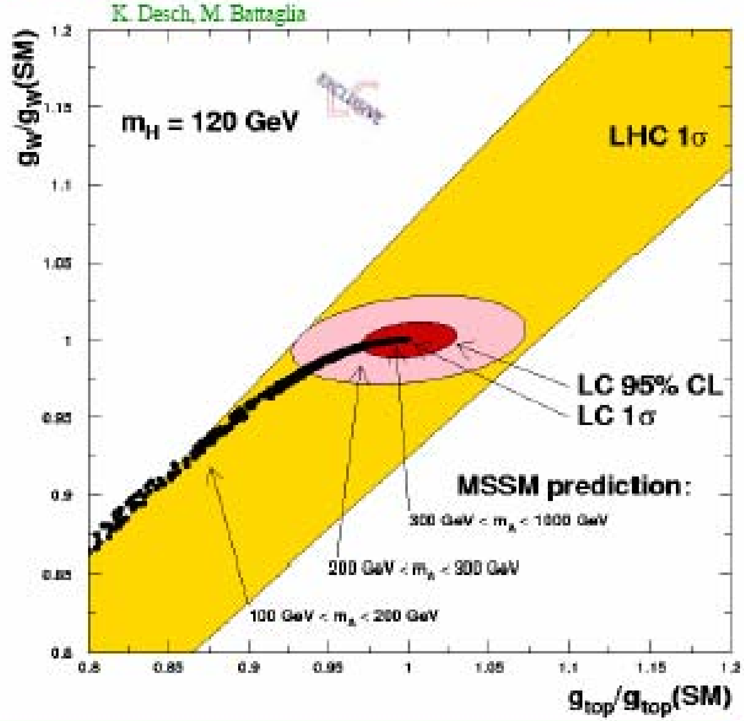
(1000/fb@800 GeV)

→

| Coupling | All | No Fusion |
|---|---|---|
| $g_{HWW}$ | 1.2% | 4.5% |
| $g_{HZZ}$ | 1.2% | |
| $g_{Htt}$ | 2.2% | |
| $g_{Hbb}$ | 2.1% | 4.1% |
| $g_{Hcc}$ | 3.1% | |
| $g_{H\tau\tau}$ | 3.2% | |

# Telling SM from MSSM Higgs - The Power of LC




- TESLA has the power to reveal the Supersymmetric nature of a light SM-like Higgs boson.
- For both machines (LHC and TESLA) it is a challenge, but TESLA seems to have better prospects in measuring Higgs boson couplings and complement LHC in that sense

# Higgs Scenarios

inspired by P.Grannis at LCWS 2000

- Tevatron/LHC sees a Higgs at 120 GeV and some evidence for SUSY:
  A LC with $E_{CM}$~350-500 GeV will measure the Higgs properties: $J^{PC}$,Width, and improve the mass measurements and the BRs.
  With high lumonosity (1000 $fb^{-1}$ it can also probe the Higgs self coupling).
  In particular it can indirectly probe the Higgs SUSY sector and predict the pseudo scalar mass to high accuracy.

- No evidence for SUSY but a Higgs is found with $m_H$~160-180 GeV.
  A LC can still measure the above mentioned Higgs parameters and probe non SM deviations. However, the Higgs decay to bb is supressed which make life harder. Perhaps a return to a Giga-Z machine will do better..

- There is a Higgs above 180 GeV and no evidence for SUSY…
  Well, what about triviality and vacuum stability????
  Maybe after measuring $J^{PC}$ its time to operate the machine as a $\gamma\gamma$ collider?
  Or perhaps think seriously of a $\mu\mu$ collider running at the Higgs pole…

- A nightmare: No Higgs , No SUSY, No nothing… LC can close some loopholes (invisibly decaying Higgs)… and go back to Giga-Z… we need to make some living…

- A festival: Higgs, SUSY, New Physics…. Well, who said we do not need a LC?

# Summary and Conclusions

- The Higgs mechanism is still the favoured EWSB scheme (SM, MSSM, …)
- But after > 20 years of searching, the Higgs boson remains elusive!

- Tantalising hints of a discovery from LEP in 2000 ($M_H > 114.4$ GeV at 95% CL)
- Precise EW data favour a light Higgs ($M_H < 202$ GeV at 95% CL)

- The Tevatron has the field to itself until 2007/8 but luminosity is big problem and b-tagging capability will not be optimal …
- The LHC is very likley to find Higgs bosons (if they exist!) in most scenarios but may not (a) find all of them and (b) will not measure detailed properties
- The $500^+$ GeV LC is *the* precision tool for making detailed studies of the Higgs boson(s) and exploring the properties

- In a decade from now we might observe the following …

# Conclusion: PDG 2014? ?

SUMMARY TABLES OF PARTICLE PROPERTIES
Extracted from the Particle listings of the
**Review of Particle Physics**
Published in Eur. Jour. Phys C3, 1 (2014)
Available at http://www.eilamgross.com

GAUGE AND HIGGS BOSONS

H

$J^{PC}=0^{++}$ [a]
Charge = 0
Mass m=120.0±0.040 GeV [b]
Full Width Γ =3.6±0.2 MeV[a]

| H DECAY MODES[b] | Fraction |
|---|---|
| bb | (67.8 ±1.6) % |
| cc | (3.08 ± 0.25)% |
| ττ | (6.8 ±0.35 )% |
| gg | (7.04 ± 0.38)% |
| γγ | (0.21 ±0.0 5)% |
| WW | (13.3 ± 6.6)% |

Or alternatively and much more interesting:

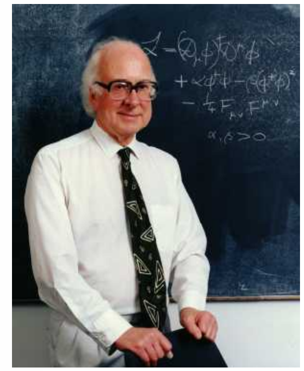
GAUGE AND HIGGS BOSONS

h

| h DECAY MODES[c] | Fraction |
|---|---|
| bb/WW | 11.06 ±0.25 |
| $R=(bb/WW)_{meas/SM}$ | 1.32 |

A

Mass m=400.0 ± 25 GeV [d]



**Peter Higgs, Nobel Prize in Physics (2013)**

[a] LC, [b] LC/LHC, [c] LC-A Global Fit, [d] LC indirectly