Higgs ~~searches~~ at LEP

Bill Murray, 30th June 2022

- What was LEP
- What did it say about the Higgs?

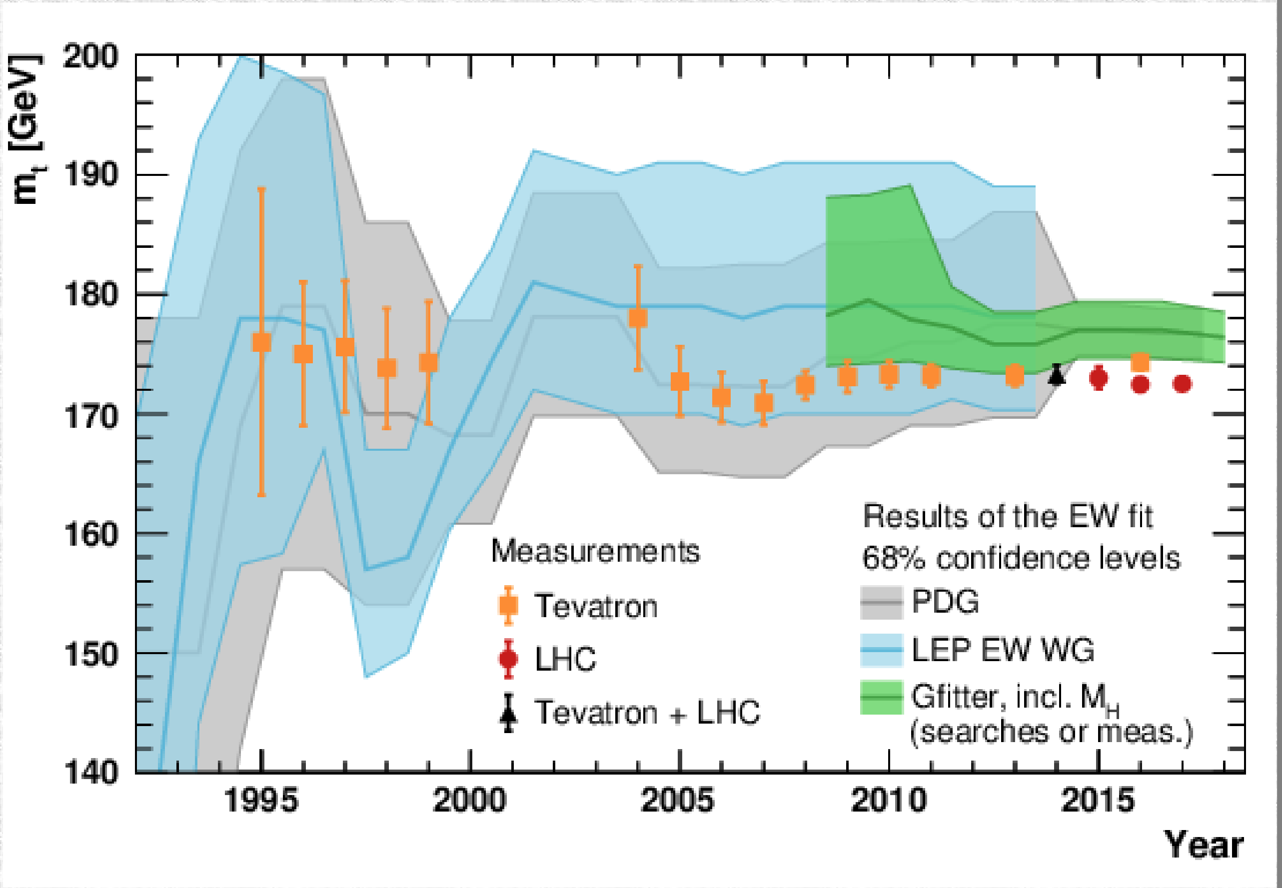
Chamonix valley

The background

- 1964 The BEH theory was born
- 1977 the b quark found
- 1983 W/Z bosons found
- 1989 LEP starts
- 1993 LEP limits $m_H > \sim 55$ GeV
- 1994 LEP EW fits predict $m_t=173^{+12}_{-13}{}^{+18}_{-20}$GeV
- 1995 Top discovered at Tevatron
- 1995 Ellis/Fogli/Lisi: $m_H=76^{+152}_{-50}$ from EW data
- 2000 LEP hints of Higgs at m_H=115GeV:
  - LEP closed
- 2013 Final LEP EW $m_H=94^{+29}_{-24}$ GeV: a sigma low

The EW fit

- One of the outputs of LEP: precision EW data
  - With SLC or more Z pole,
  - And Tevatron for m_W and optionally m_t
- Here m_t is predicted
- This is why the new CDF m_W is so shocking
- All my physics life the EW fit just works



What was LEP?

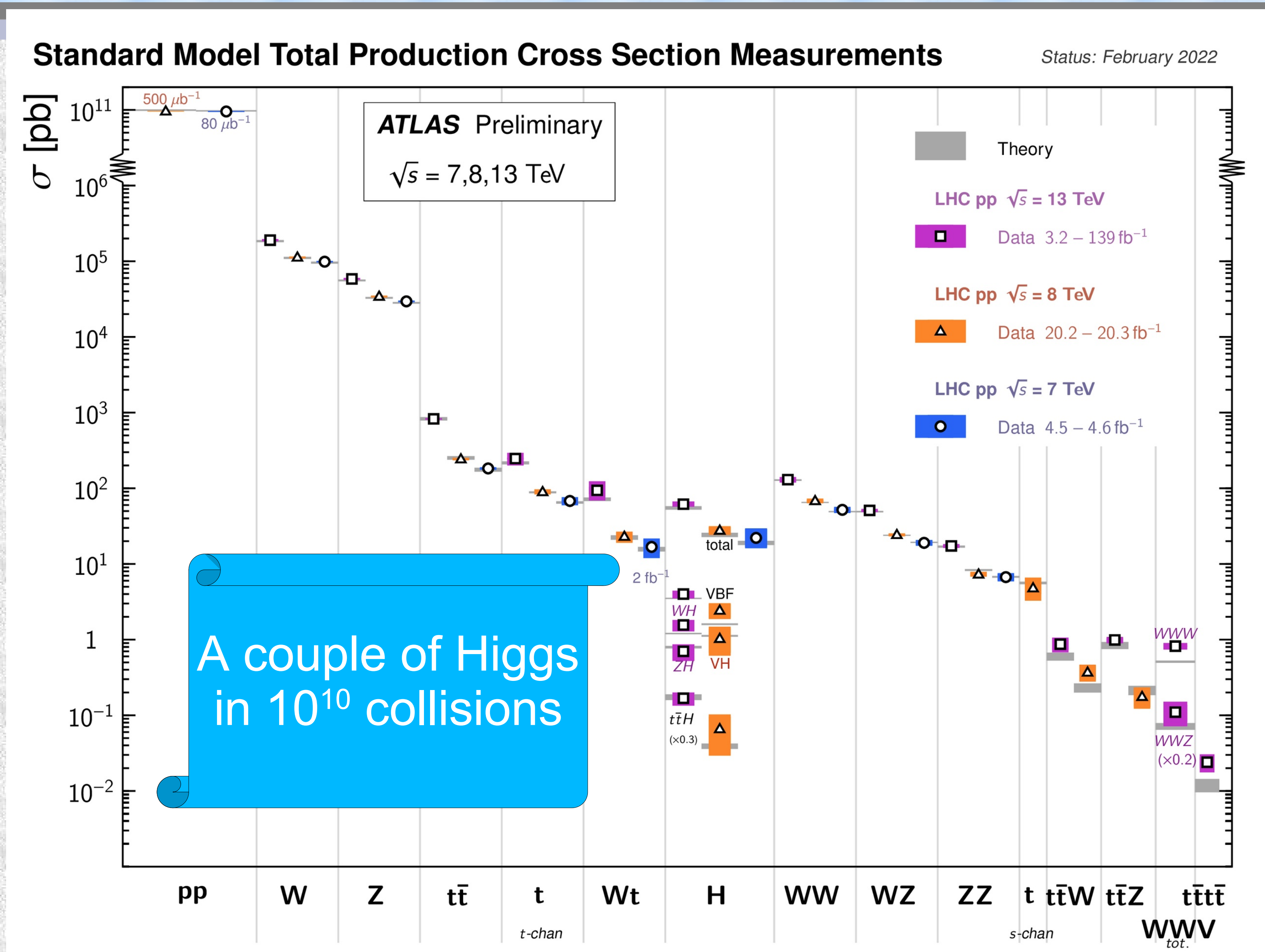
- Highest energy electron positron collider
- 1989 first beam
- 1989-95: LEP 1
  - The Z years
- 1996-99: LEP 2
  - The W years
- 2000: The Higgs year
- Nov 2000: dismantling

Circumference: 27 km – the LHC tunnel
Energy range: 20 to 104.5 GeV

Higgs production at LEP?

- "Higgs physics at LEP 1" (1989) considered 3 process:
  - Toponium decay: $t\bar{t} \rightarrow H\gamma$
    - Dismissed as toponium *likely* to be too heavy for LEP I
  - $Z \rightarrow H\gamma$
    - Clean signature but at most tens of events
  - $Z \rightarrow HZ^* \rightarrow Hf\bar{f}$
    - We have a winner!
    - Hee/Hμμ favoured – precise mass reconstruction
    - Hνν "interesting, but only for m_H<20 GeV"
    - Hqq "overwhelming QCD multijet background"
      - "Maybe $b\bar{b}b\bar{b}$ mode can be identified with a vertex detector?"
  - Conclude 10^7 Z's allows limits around m_H>55 GeV
- At LEP 2 $ee \rightarrow Z^* \rightarrow ZH$ was clearly dominant
  - With a small contribution of VBF: $ee \rightarrow \nu W \nu W \rightarrow \nu\nu H$

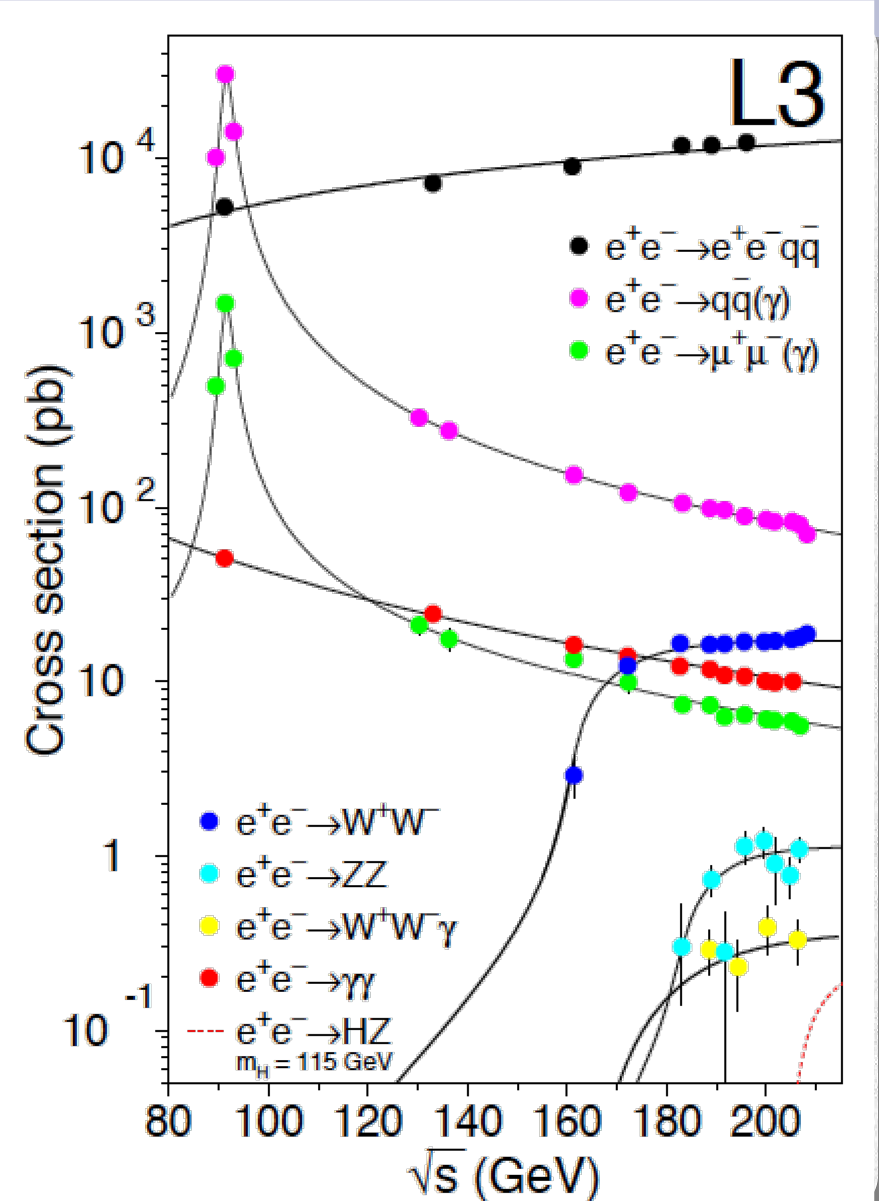
Cross-section comparisons: LHC



A couple of Higgs in 10^{10} collisions

Cross-section comparisons: LEP

- LEP at maximum energy expected one Higgs in every 10^5 collisions for m_H=115
  - A factor million better s/b than LHC
- On Z peak most events were Z^0.
- And that ee→eeqq spectrum is very soft, like LHC minbias



LEP experimental environment

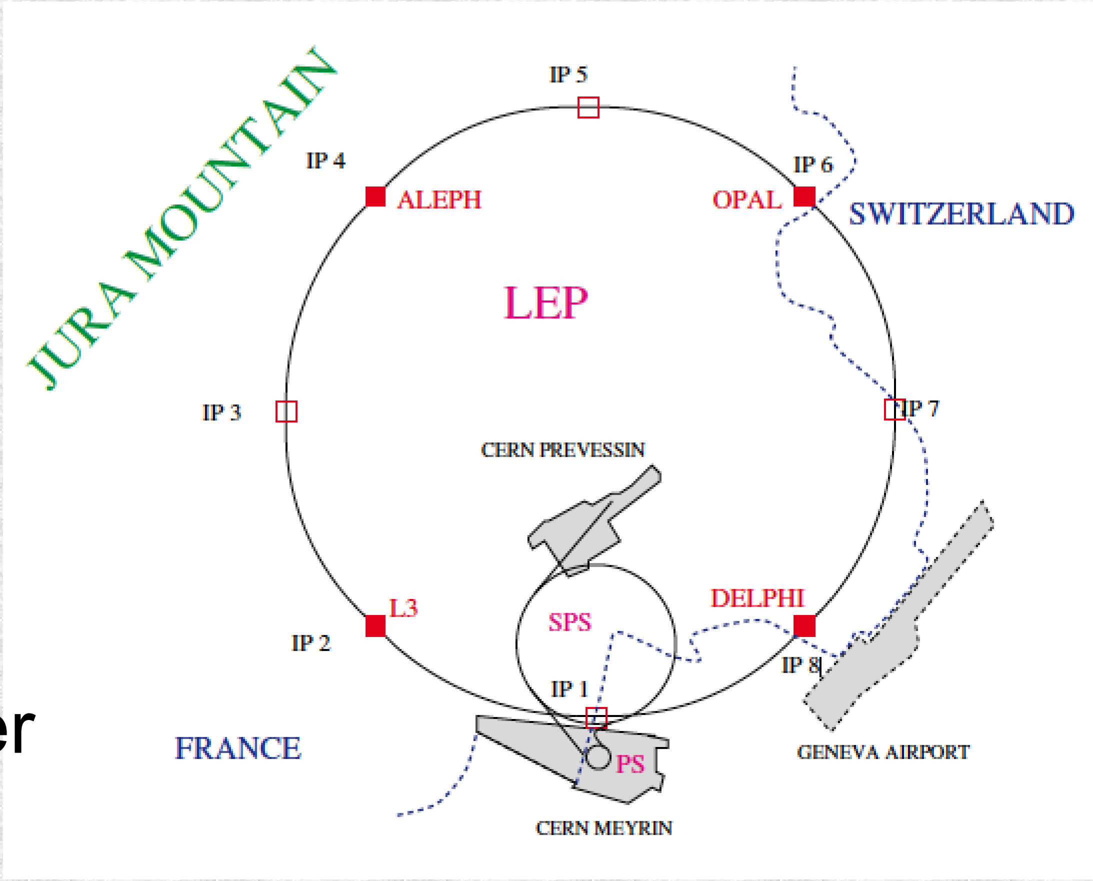
- Revolution frequency is 11.2 kHz same as LHC
- But with 4 bunches (trains) not ~2800
- So 17 μs inter-bunch spacing
- And μ about 0.00005!
- Cross-sections and luminosities far below LHC
  - 0.2fb^{-1} in the best year
- We did not see it as easy. DELPHI trigger paper:
  - "To cope with high luminosities and large background rates the trigger system is structured into four successive levels...aim of maintaining the data logging rate close to 2 Hz…"
- LEP papers rarely mention the trigger.
  - Rates are assumed effectively 100%

Data driven backgrounds?

- No thanks!
- Generally simple events made MC more reliable
  - No pileup
  - No underlying event
  - ‘No’ PDFs
  - Good s/b
- Sam Ting: “Every event at a lepton collider is physics, every event at a hadron collider is background”
- Work need to match simulation to data
  - Calorimeter response
  - Tracking tails hard to get right
    - So adjustment of MC track parameters to match data
  - Muon punch-through always tricky
- Set of corrections to MC was the normal approach

4 experiments at LEP

- ALEPH:
  - Big TPC, (few m drift)
  - sampling calorimeter
- DELPHI: my expt
  - Innovative, technology driven. TPC, silicon vtx, 3D calorimeter, RICH
- L3
  - Excellent EM calorimeter & muons, little tracking
- OPAL: my first expt
  - Reliable, solid, works.
  - Jet chamber giving good PID



Daniel Treille, 1981

Planning Expt DELPHI

Big discovery for 1980's: No top! Testing EW was excellent

Realistic Luminosity: He meant 2pb^{-1} per year. Actually 65pb^{-1} achieved on the Z

Present feeling:

1. Work on top of Z_0, but keep in mind the toponium. Testing electroweak is not trivial.
2. With realistic assumptions on L, the physics domain has been shrinking but is still wide
3. one should keep rather ambitious goals (a general detector): the possibility to do spectroscopy, identification or energy correlation inside jets, ...

$\frac{\Delta p}{p}$, resolution in z, granularity, π_0 and η reconstruction, e identification, ...

(4) leading particles identification ($K^{\pm}, p, \bar{p}$) and detection (K_0, Λ) and single γ identification are still arguments in favour of arms; however low rates and/or unclear physical interest weaken the point "forward" arms should be considered as well as 90° arms

(5) particle identification for spectroscopy and jetology could well after all be achieved by improved dE/dx methods. it would be good to start with an atmospheric pressure central detector and put pressure afterwards

(6) machine backgrounds may be decisive in the choice and design of the central detector. for instance the attractive solution of a TPC has to be examined in this respect.

(7) detecting short lived particles looks feasible on paper. its degree of usefulness and its realism ~~have still to be appreciated~~

(8) main instrumental concerns presently are:
- central detector
- calorimetry — projection chamber
- vertex detector

"Arms". 4π detectors are a novelty

Machine backgrounds were low: TPC worked well

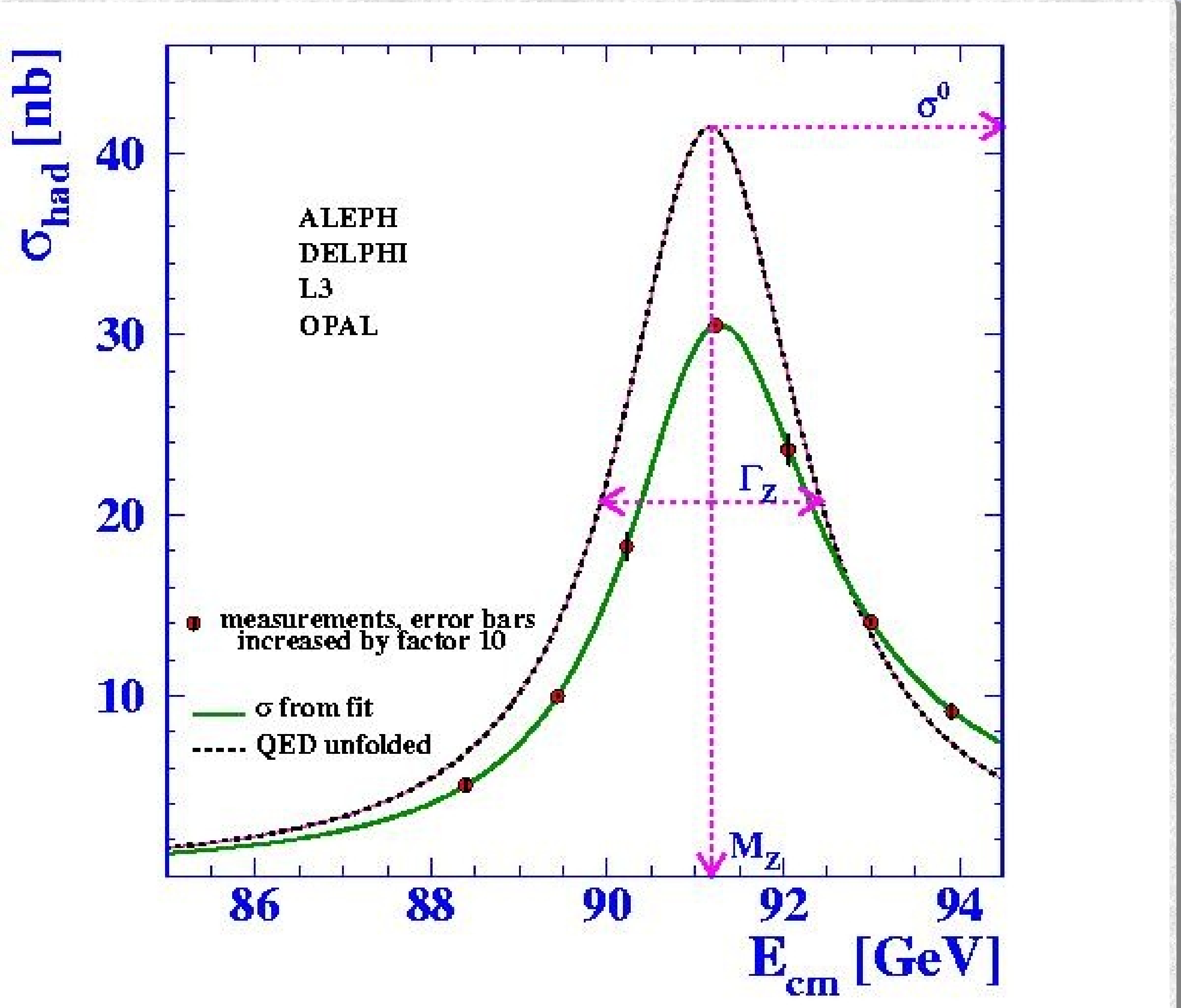
A vertex detector. Silicon planned for

LEP 1

- 4 milllion Z bosons recorded by each experiment
- Can they see the $Z \rightarrow Z^{*}H \rightarrow f\bar{f}H$ decay?

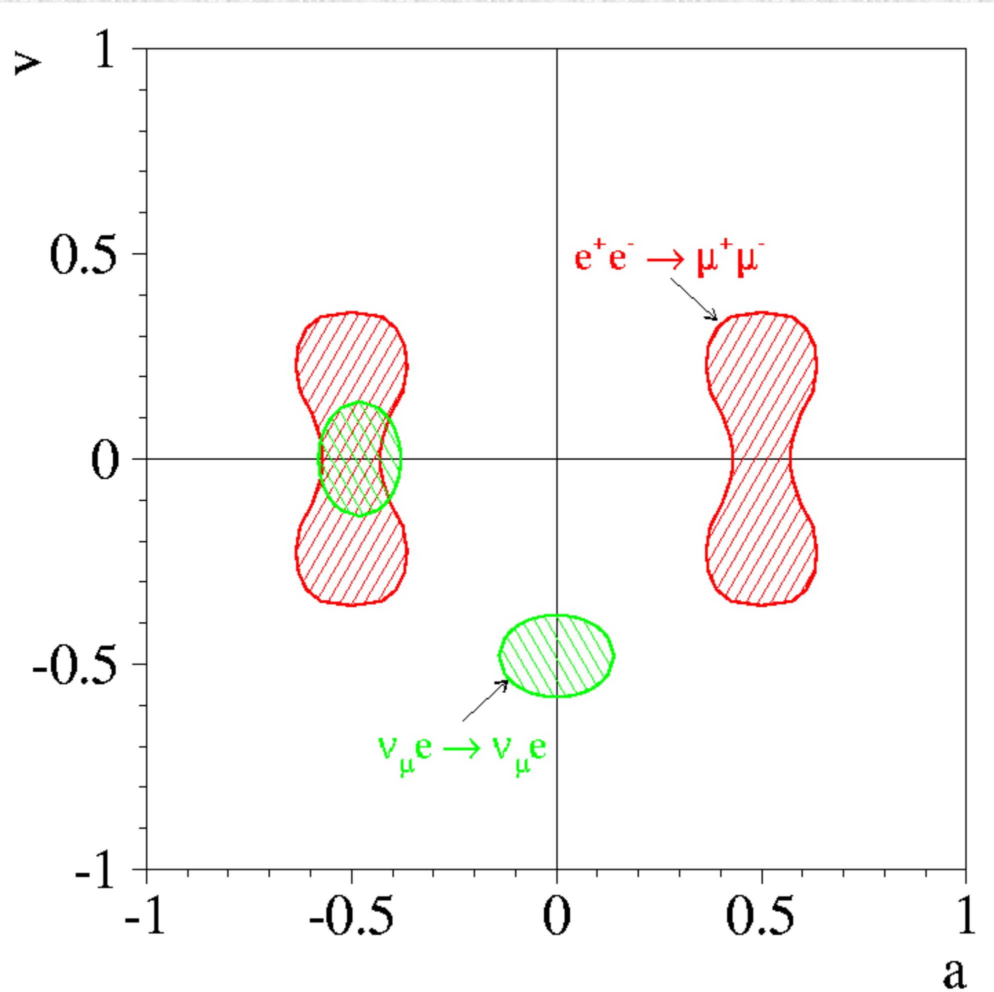
LEP 1 Z physics

- Yellow Report 'Z physics at LEP 1' called for 11 point scan with μ pairs
- Control of efficiency by cross-checks allows multihadrons
- 20 times high rate
- **Luminosity monitoring to 1 per mille critical**
- synergy with theorists!

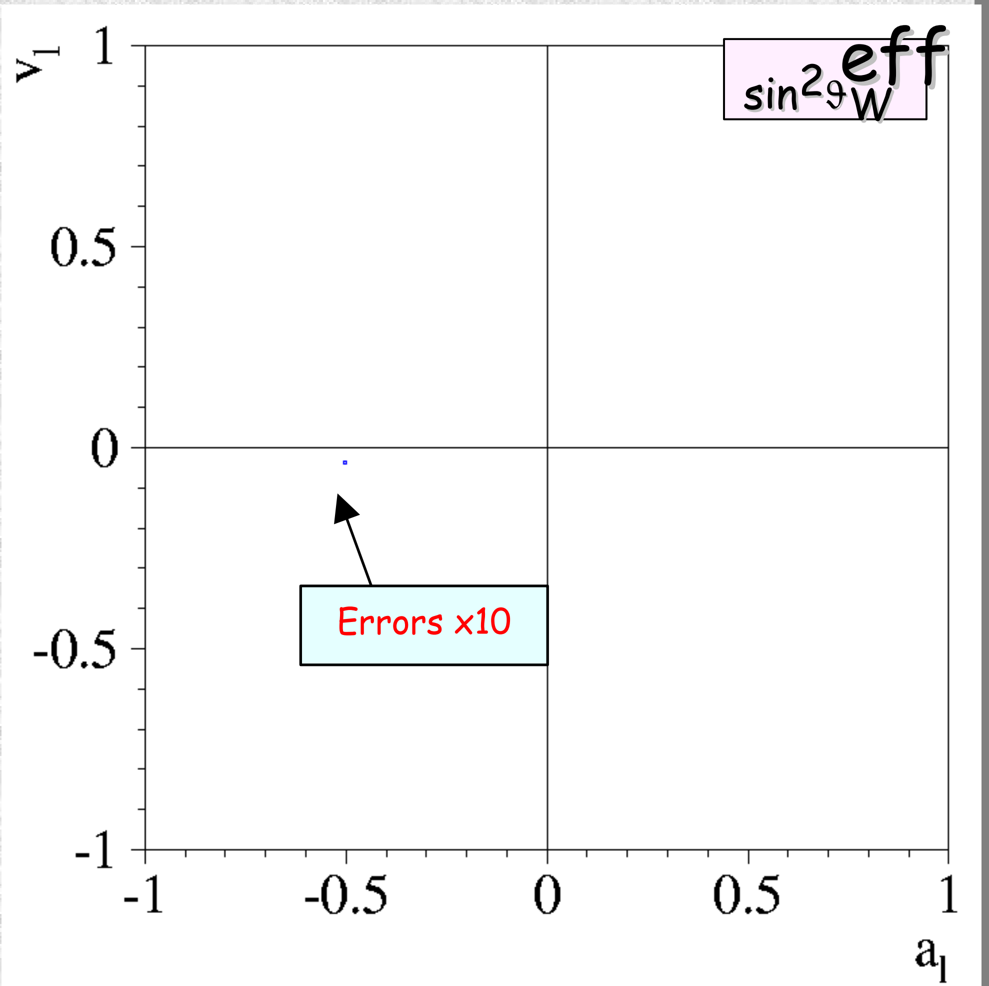


Measurements of Z coupling

v & a before LEP and SLD



v & a after LEP and SLD



- Totally revolutionized the field

Higgs Searches at LEP 1

Clean Z^* decays (ll, $\nu\nu$) used

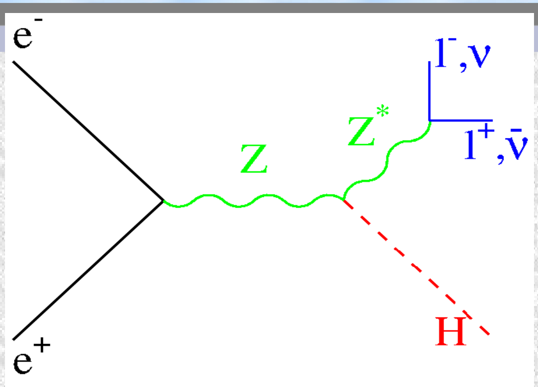
Higgs decays modes mass dependent:

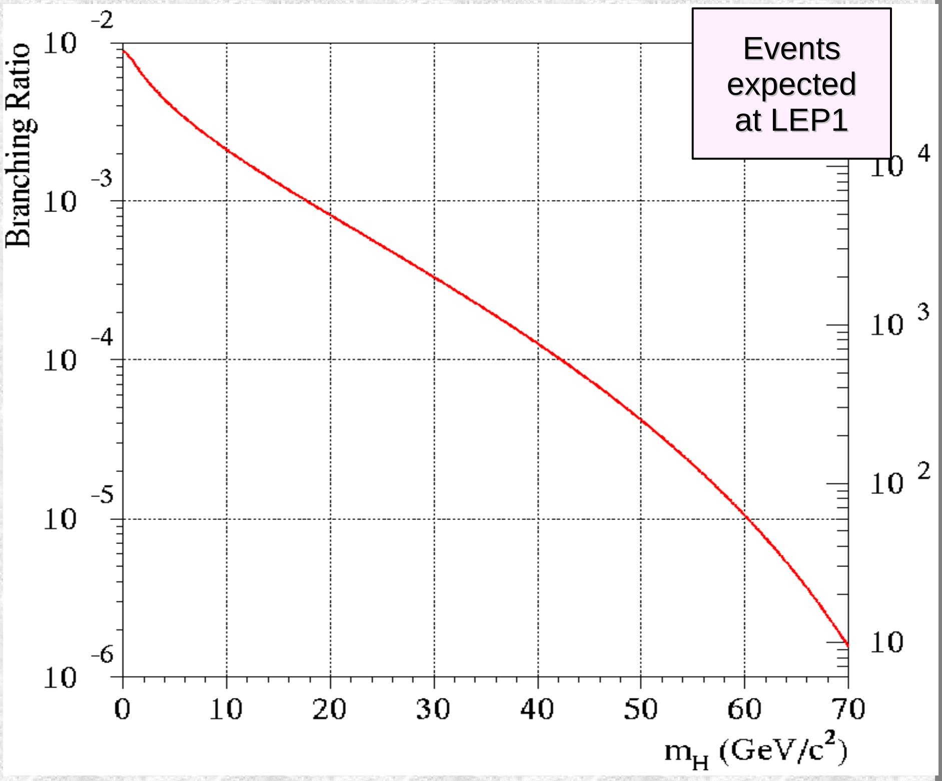
Stable, $\gamma\gamma$, ee, $\mu\mu$, $\pi\pi$, $\tau\tau$, bb

Prior to LEP only some patchy constraints

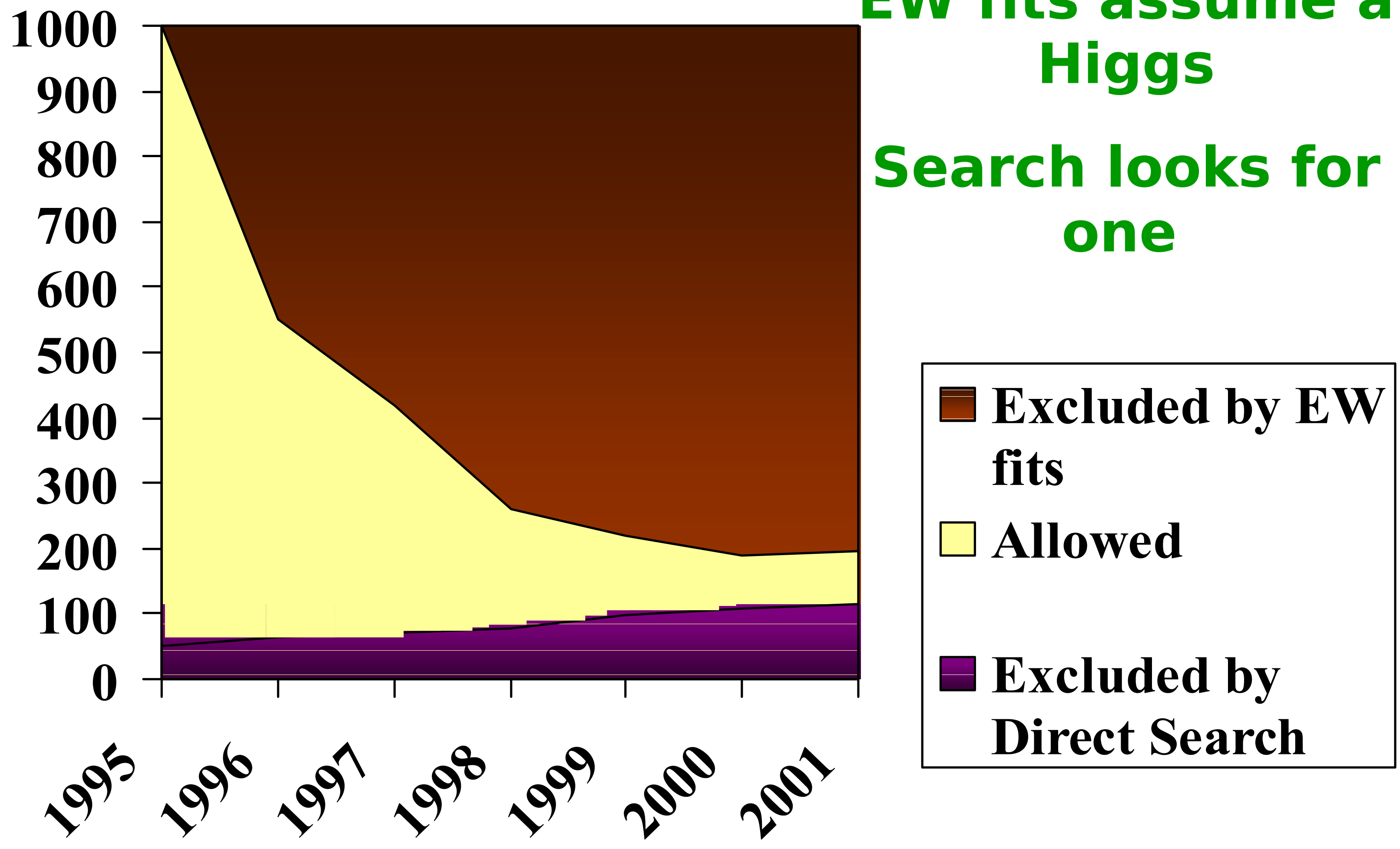
The mass range to 0 now excluded, no holes.

$0.0 < m_H < 65\ \mathrm{GeV}/c^2$
Excluded at 95% C.L.





LEP II: Closing in on the Higgs!



EW fits assume a Higgs

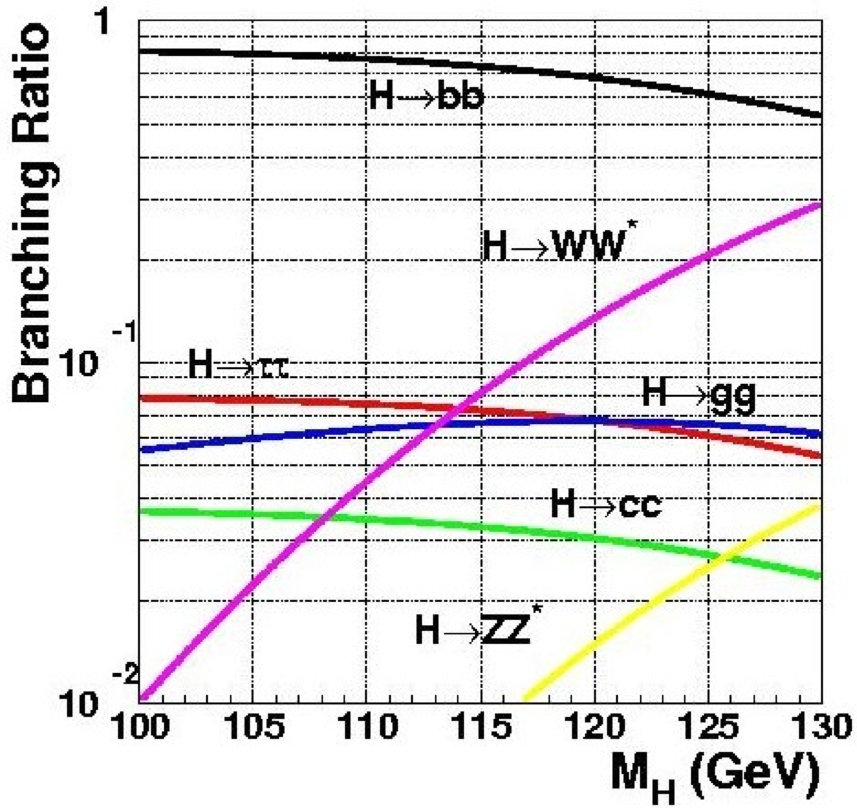
Search looks for one

After A. Wagner, ICHEP 2000

LEP II Higgs channels

Decay mode	*Br*
bb	73.6%
$\tau\tau$	7.2%
Gluons	6.6%
ww	8.1%

Higgs decays, 115GeV

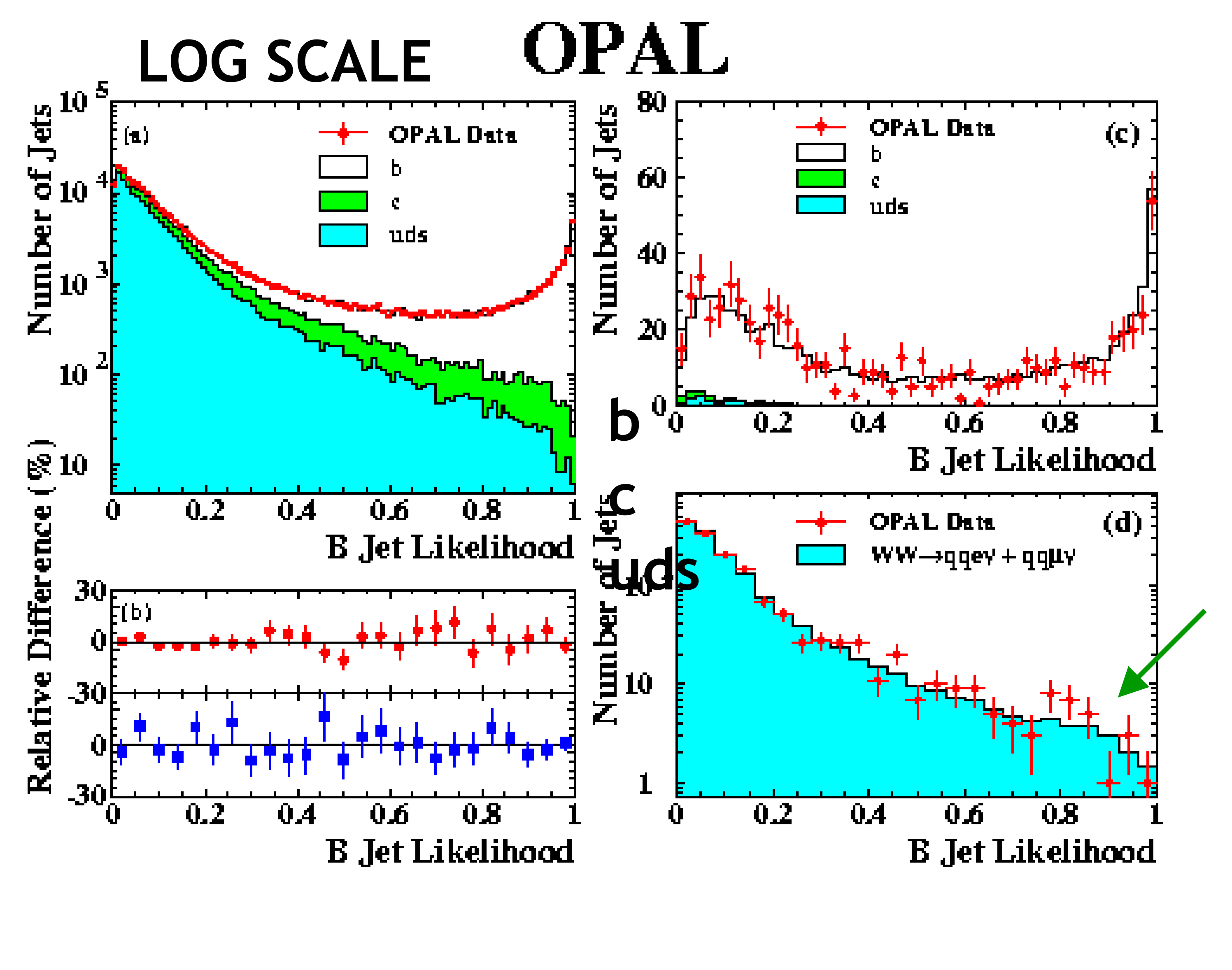


Higgs Decay	Z decay	Fraction
bb	qq	51.50%
bb	$\nu\nu$	14.70%
any	ll	6.70%
bb	$\tau\tau$	2.50%
$\tau\tau$	qq	5.00%
Total		80.90%

Most decays included in search.

c/f ~ 0.3% used at LHC

B-tagging – crucial step



Tag of b's reduces many backgrounds

Semi-leptonic W's dangerous

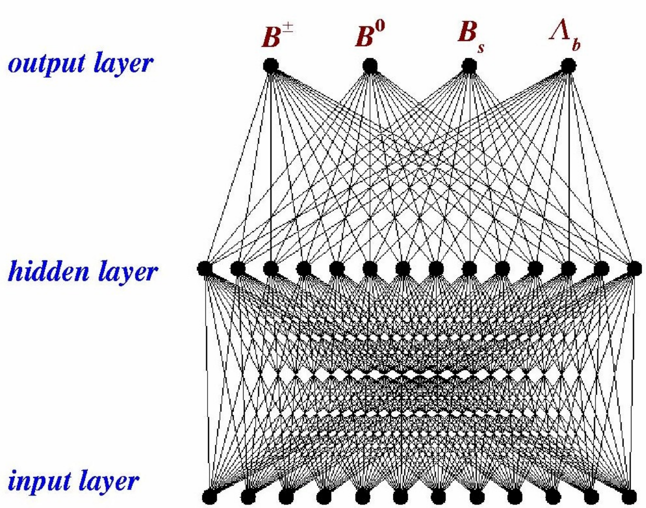
Mis-tag is well controlled

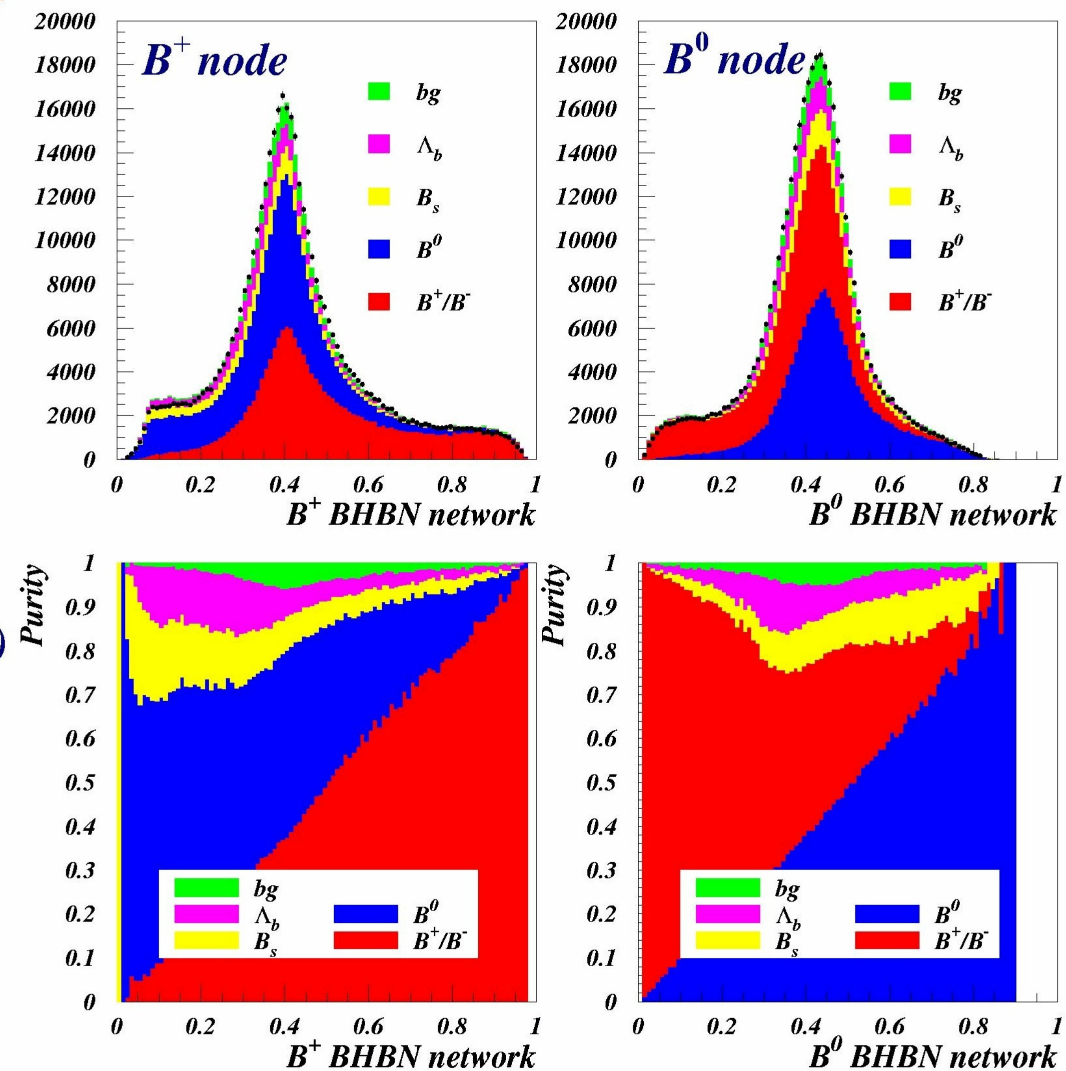
Separation and enhancement of B−Hadron−Species:

⇒ neural network

some input variables:

- *Vertex charge*
- *Error on vertex charge*
- *Number of charged pions per hemisphere*
- *Reconstructed energy of the hemisphere*
- *Probability that identified kaon/pion stems from fragmentation or B−decay*
- *Quality variables (e.g. hemisphere quality)*

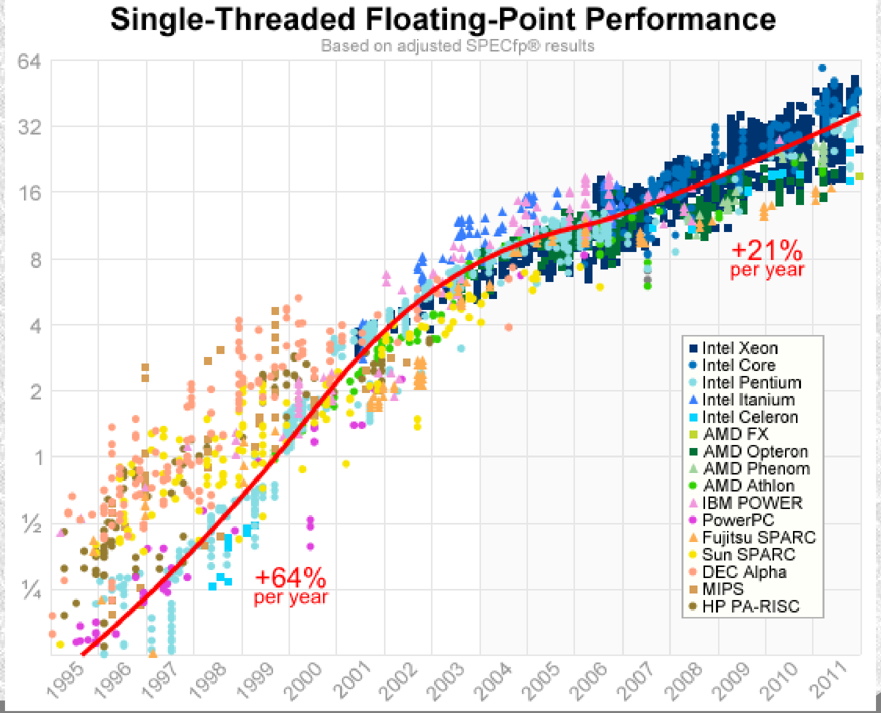




NN now LEP legacy

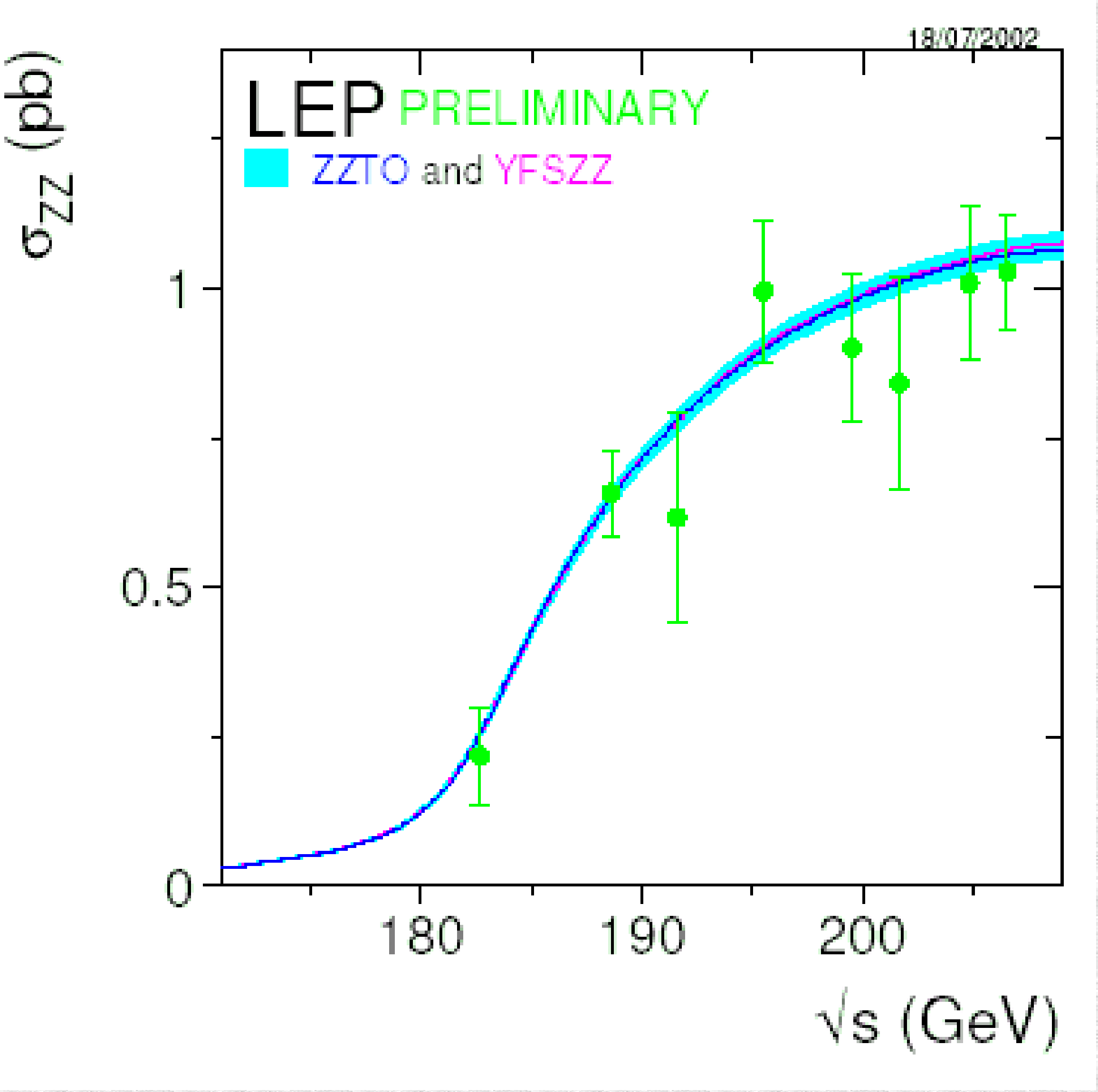
Why did NNs fall out of fashion?

- Hornik, Stinchcombe and White (1989) "Multilayer Feedforward Networks are Universal Approximators"
- Proved 1 hidden layer allowed *any* response
  - But few people appreciated it made it hard to train
- Training is expensive and in the 1990s computers were less performant.
  - Especially for deep networks
- So typically we used suboptimal 1 hidden layer
- BDTs replaced NN after LEP



ZZ cross-checks

- ZH and ZZ can look very similar
- B-tag important for ZZ selection
- Proof that this very similar channel can be measured
- A major background is under control

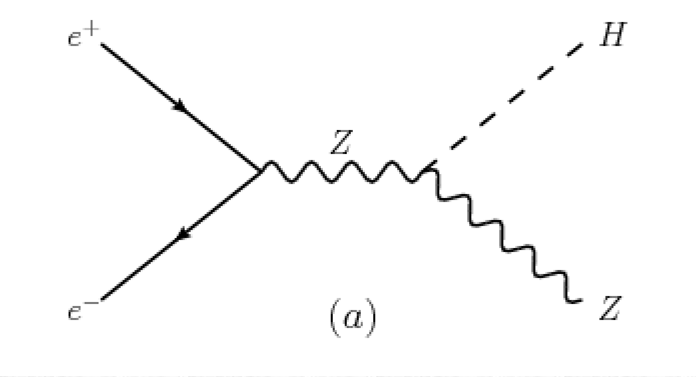


LEP 2 1995 - 2000

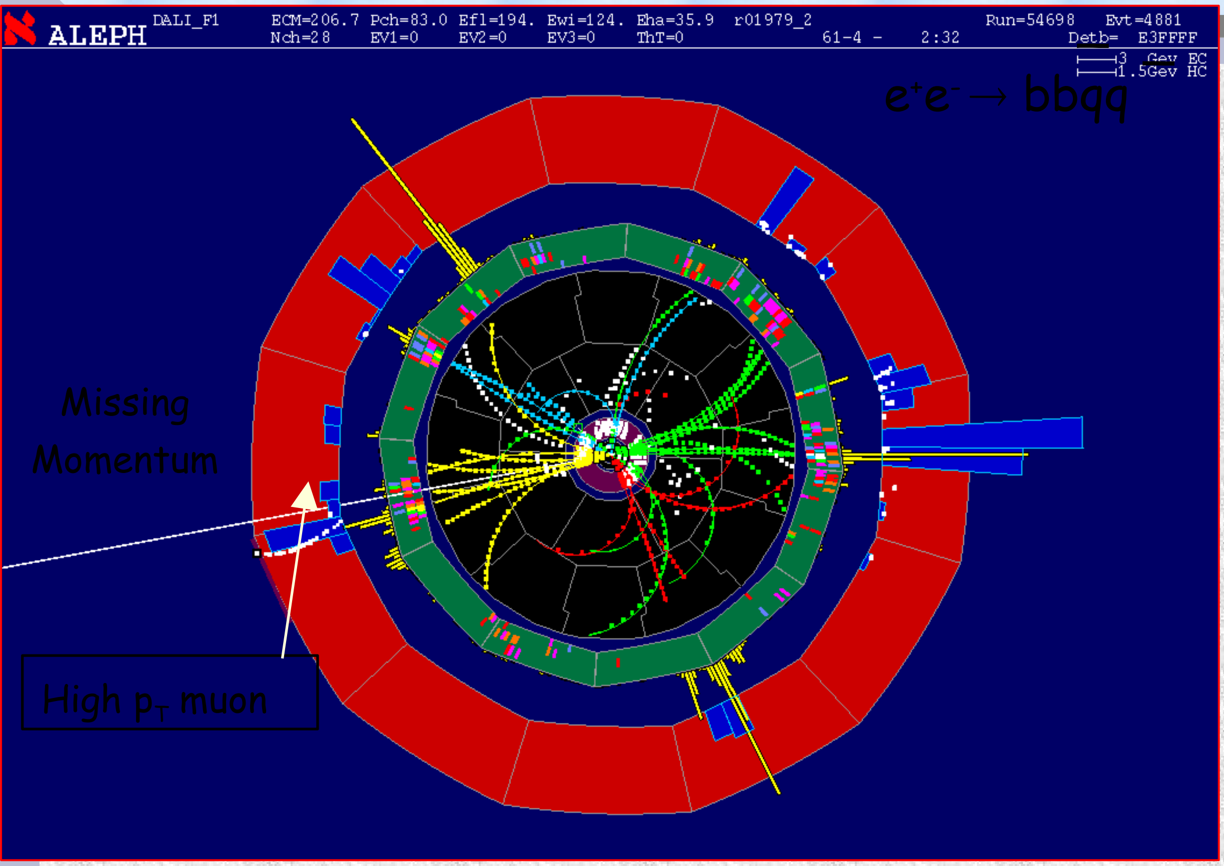
- Energy raised gradually to 208 GeV in 2000
- Searching for $e^+e^- \rightarrow ZH$
- No sign in previous years
- Needs enough energy to make both
- The Z mass is 91 GeV/c^2
  - The approximate reach:

$$m_H \leq E_{CoM} - m_Z - 2$$

- So able to make the Higgs boson if it weighs less than 115 GeV.
  - Would reach be enough?



Summer 2000 excitement!



- 2 or 3 events looking like ee→ ZH→ $(q\bar{q})(b\bar{b})$
- The quarks each produce a jet of hadrons
  - Coloured differently in the event display
- Could it be m_H~115GeV?
  - Or just ZZ?
- Need to calculate probability of seeing what we did under different hypotheses

Culture clash

- The evidence rested on a handful of events.
  - In some cases the interpretation was changed
- A younger generation, which I was once, felt that the statistics was the important thing: we had to rigorously apply the methodology defined
  - As we did the work….this is what the world saw
- An older, wiser, generation studied the candidates
  - One DELPHI event, a candidate for Z→ee, H→ bb was obviously a radiative Bhabha. Rules were twisted and it was dropped. Good call.
  - Another DELPHI event Z→qqH→bb was known as ‘the one that got away’. The chosen pairing said m=97, the alternate was near 115GeV.
  - The smell of the events mattered.

Maximum likelihood pitfall

- Using the likelihood for each event, s_i/b_i, is the optimal way to distinguish two hypotheses.
  - But only if you can calculate s_i and b_i
- Easy enough if you just have one variable (mass?)
- But in multi-dimensional spaces it is hard to obtain
  - Needs a lot of MC if you fill a space by brute force.
- LEP Higgs was mostly analysed in a 2D space:
  - e.g. ($m_{H,}$ NN) or (mH,b-tag)
  - With maybe an assumption that the two were not correlated $\rho = \rho(m_H, NN) \simeq \rho(m_H) \times \rho(NN)$
- This approximation exaggerated the 115 GeV hint
  - Correlations initially ignored had to be allowed later

Curse of improving data handling

- The price of transistor and ability to process data keeps improving
  - This must make computing easier?
- Actually it makes data taking easier
- But naive likelihood calculation time rises with N^3
  - The computing that allowed you to take data increasingly struggles to process it
- Even the best processing needs O(NlogN)
  - You have to analyse those N events..and compare to some sum of expectations.
- LEP was <u>lucky</u> it was able to use brute-force likelihood as much as it did

LEP Higgs working group

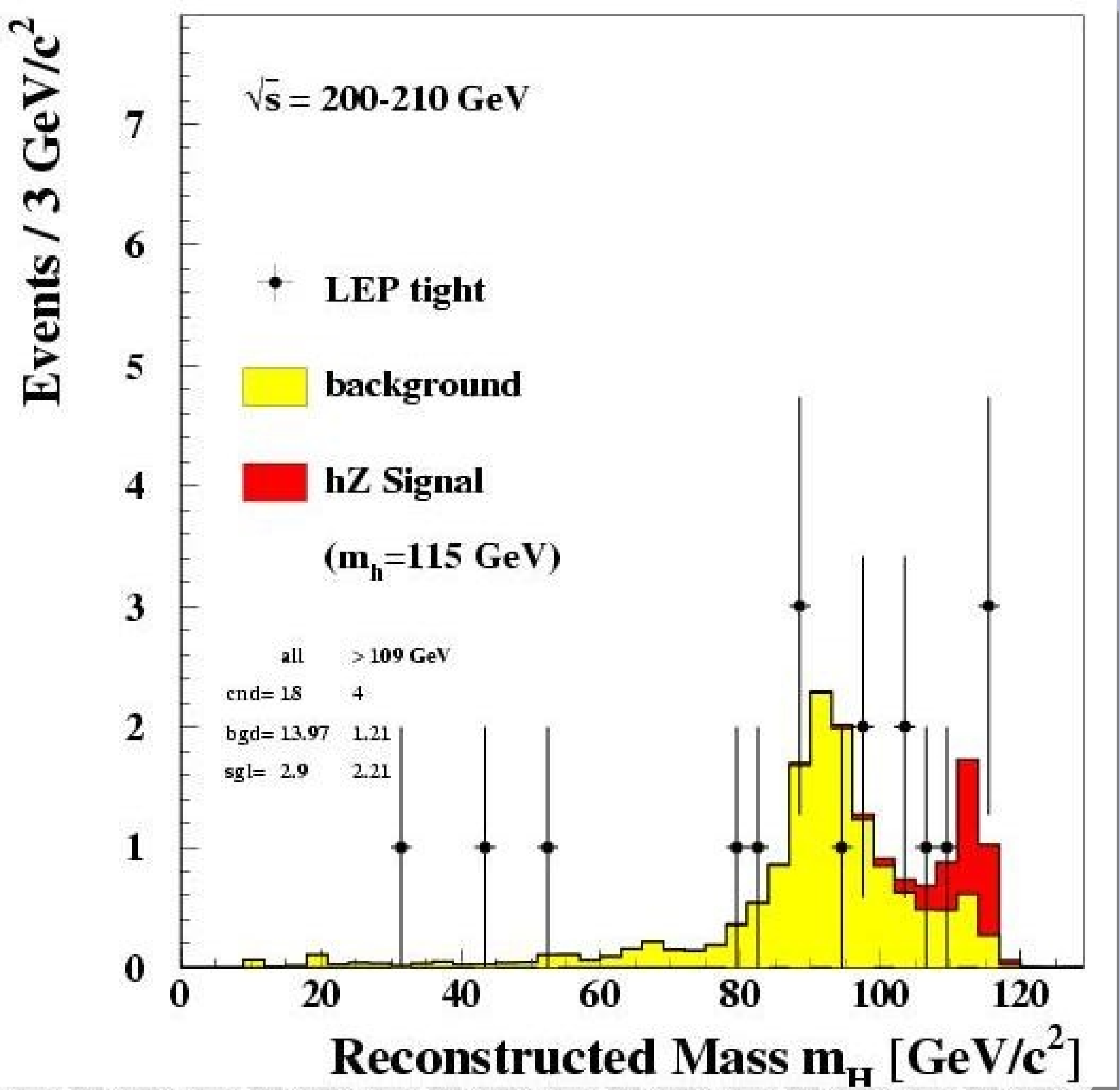
- Working group set up to handle both:
  - Agreement on theory predictions
  - Combination of experimental data between four groups.
- There were a few ‘trusted’ theorists
  - I think it was just Heinemeyer, Pilaftsis, Weiglein
  - A great bunch – but created tension
- LHC Higgs WG had neither data, nor a restricted theory membership.
  - Rei will discuss this

LEP HWG stats

- Each experiment had its own statistics tools
  - Mostly not based on likelihoods
  - To compare we wanted 95% to mean something
    - We wanted tightest limits (on average)
    - While falsely excluding at most 5% of the time
  - Note: these are frequentist tests
  - But also we ‘knew’ you cannot exclude a signal with less than 3 expected events
- CLs was result: CLsb/CLb
  - CLb: chance to see so little if background only.
    - Averages 0.5 if no signal
  - CLsb: same if signal present:
    - ensures the false exclusion
- Test statistics of LR gave most powerful limits

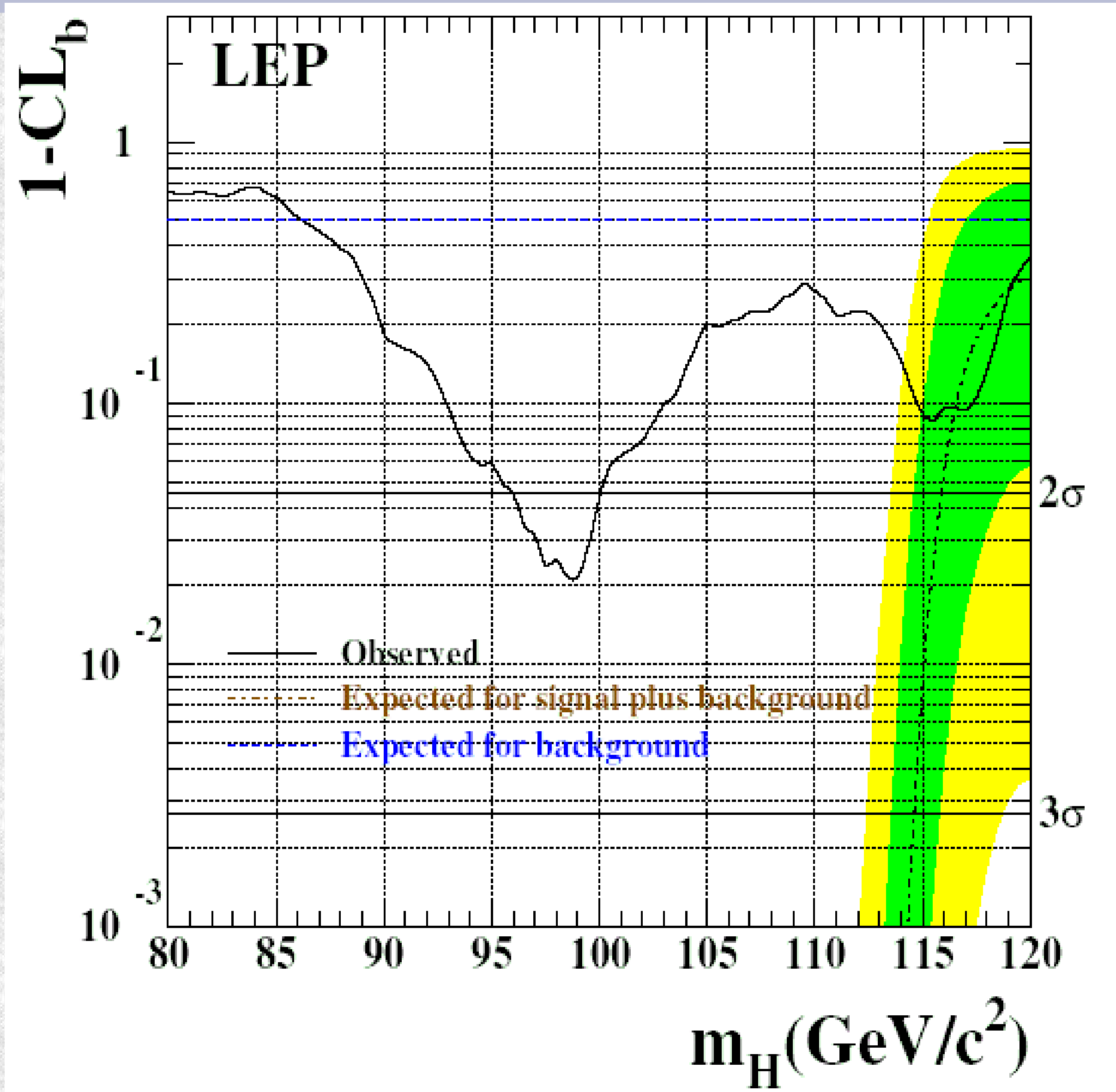
2000: Combine all LEP data

- Plot of all Higgs candidates masses
  - Yellow is background ZZ
  - Red m_H=115
- 9% (~1.7σ) chance of seeing so much from background
  - Was this it?
  - LEP closed in 2000
    - Leaving agonizing uncertainty
- m_H>114.4GeV



LEP p-value ("1-CLb")

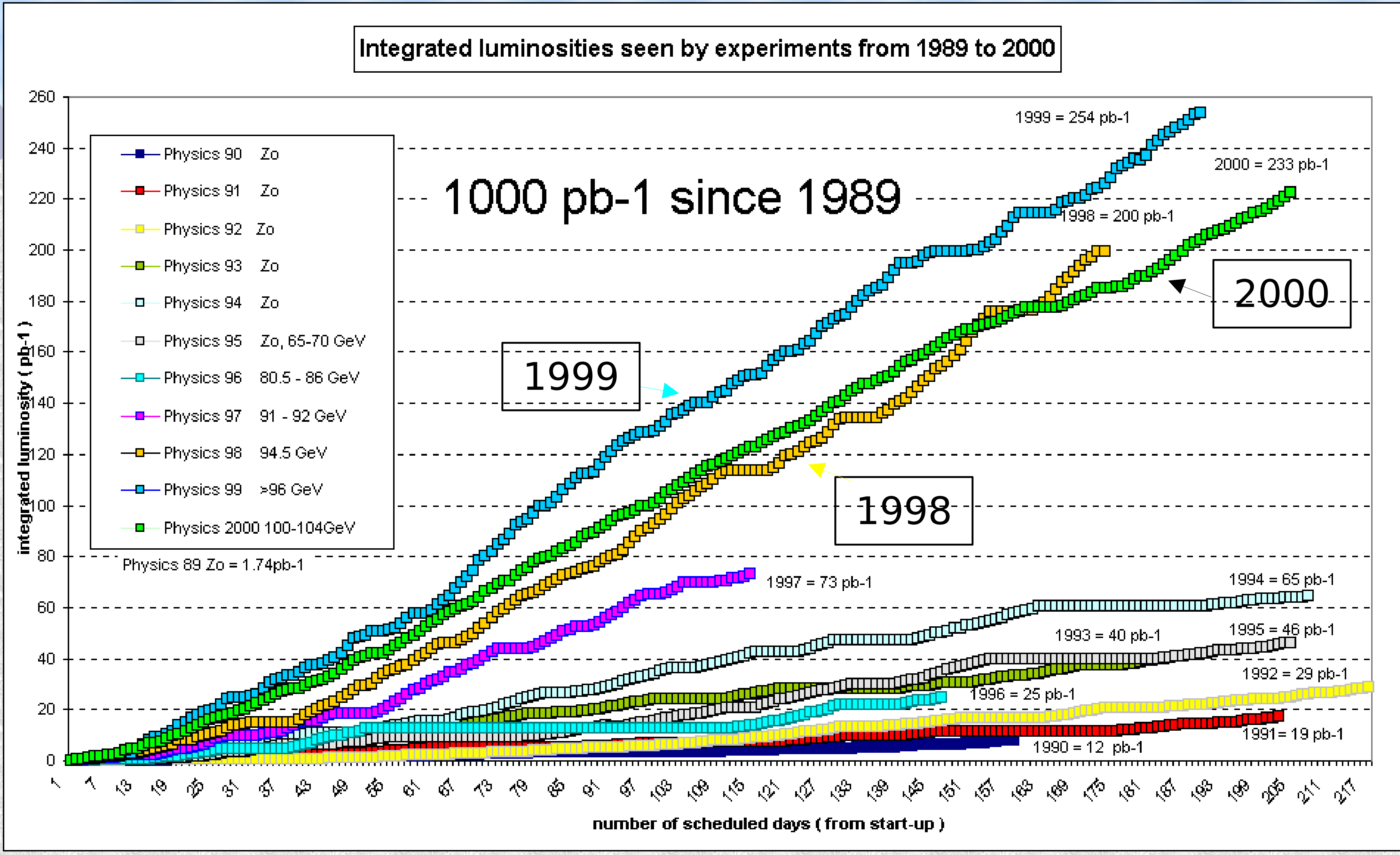
- Probability of excursion at 115 GeV is 9%
- More extreme fluctuation at 98 GeV dismissed as SM Higgs would have been clearly observed there
- What is the mass range for look elsewhere?
  - We argued it was



The LEP Legacy

- LEP was closed after 2000
- M_H>114.4GeV was huge step
- The hint at 115 GeV proved to be a fluctuation
  - But the tools developed into the LHC Higgs approach
- The EW fit established the Higgs
  - Especially after Tevatron top discovery
  - Consistency of m_W, m_t with all the angular and rate information of the Z peak
    - Even today LHC EFT fits are proud when they can say 'We beat the LEP constraints'
  - Alternate models like technicolor were excluded
- Next is the Tevatron
  - See Ben Kilminster now!

minosity and energy performan

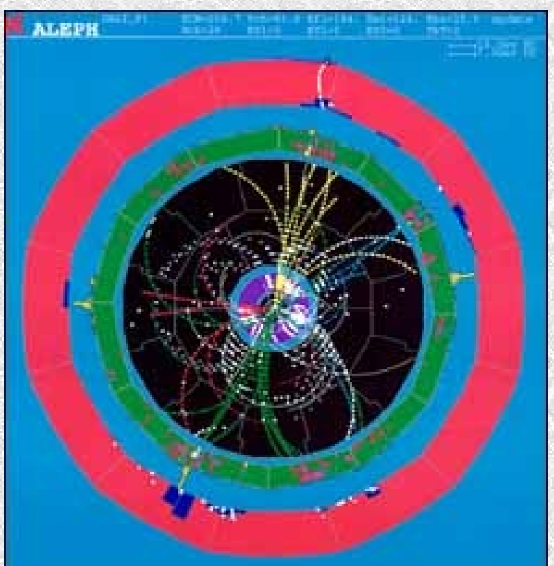


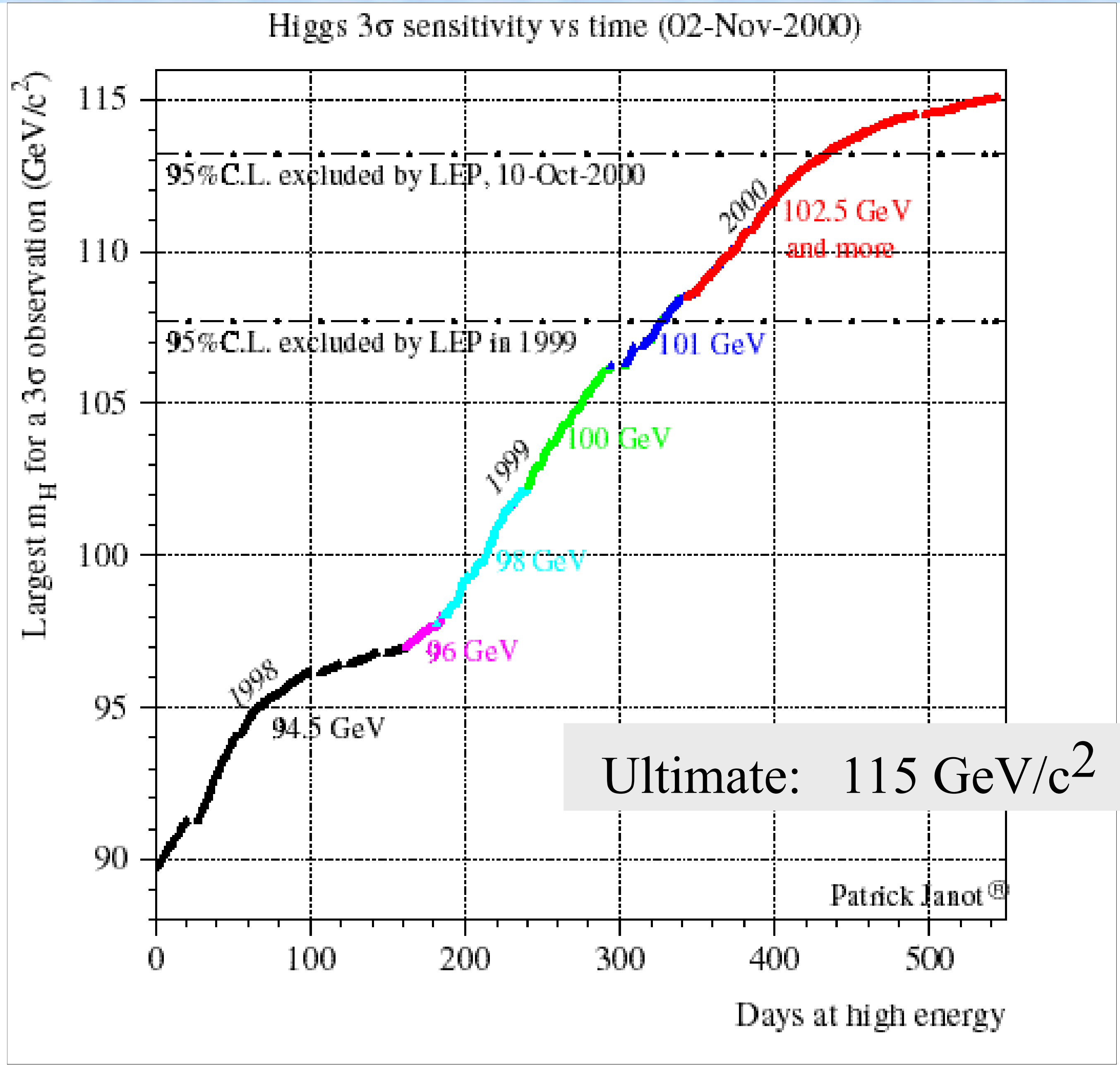
70% of total delivered luminosity above 94 GeV and in the final three years

Energy reach and the Higgs

Luminosity
+
Energy

Discovery reach for the Higgs





Ultimate: 115 GeV/c^2

Z mass

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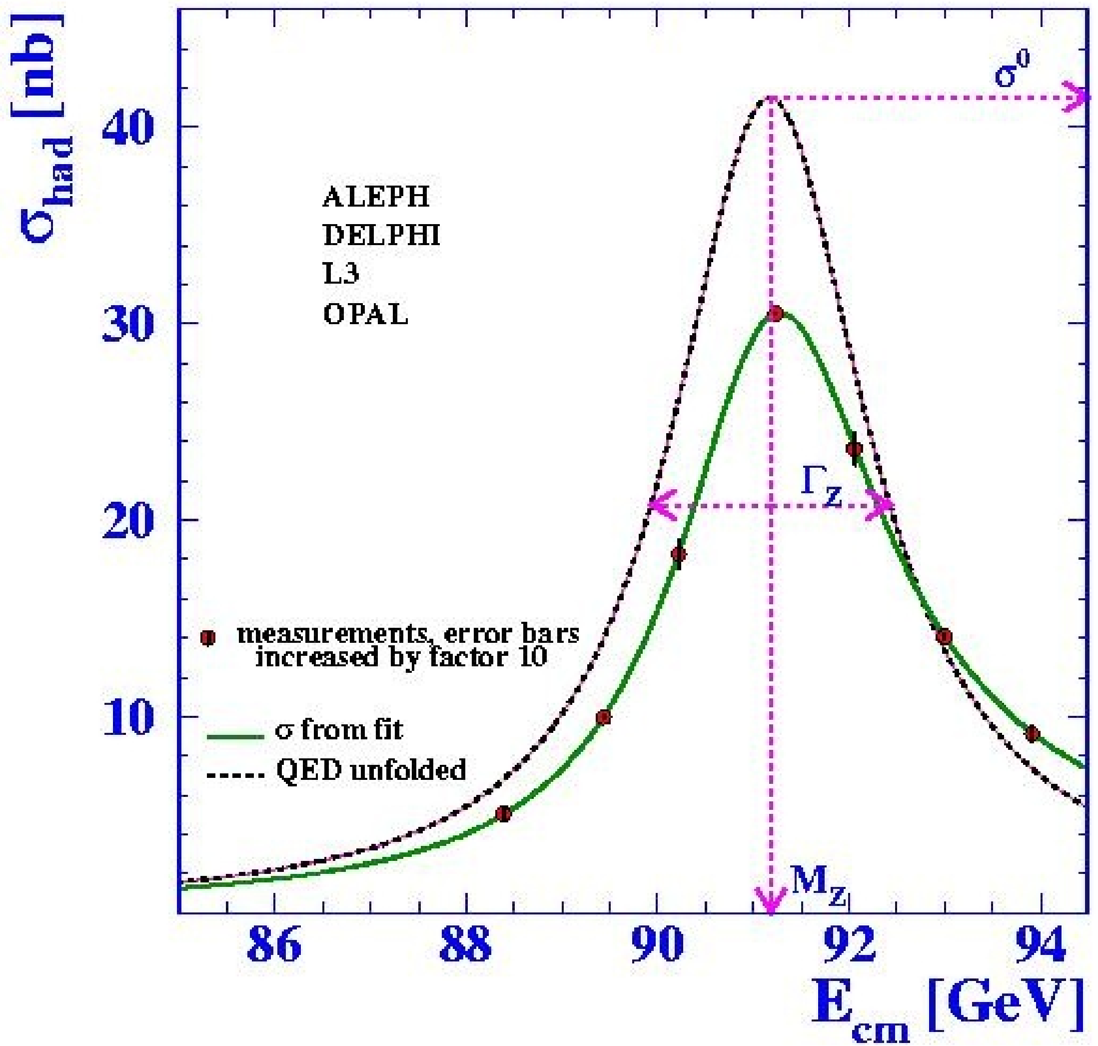

LEP Higgs working group

- A few representatives per experiment
  - And a handfull of picked theorists
- Set up to handle theory predictions and combinations of results of 4 expts.
  - Each experiment had its own statistics tools
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  - To compare we wanted 95% to mean something
    - Many tests & comparisons made
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- CLs was proposed by Alex Read