Karlsruher Institut für Technologie

Higgs Boson Physics – historical Searches for the Higgs Boson

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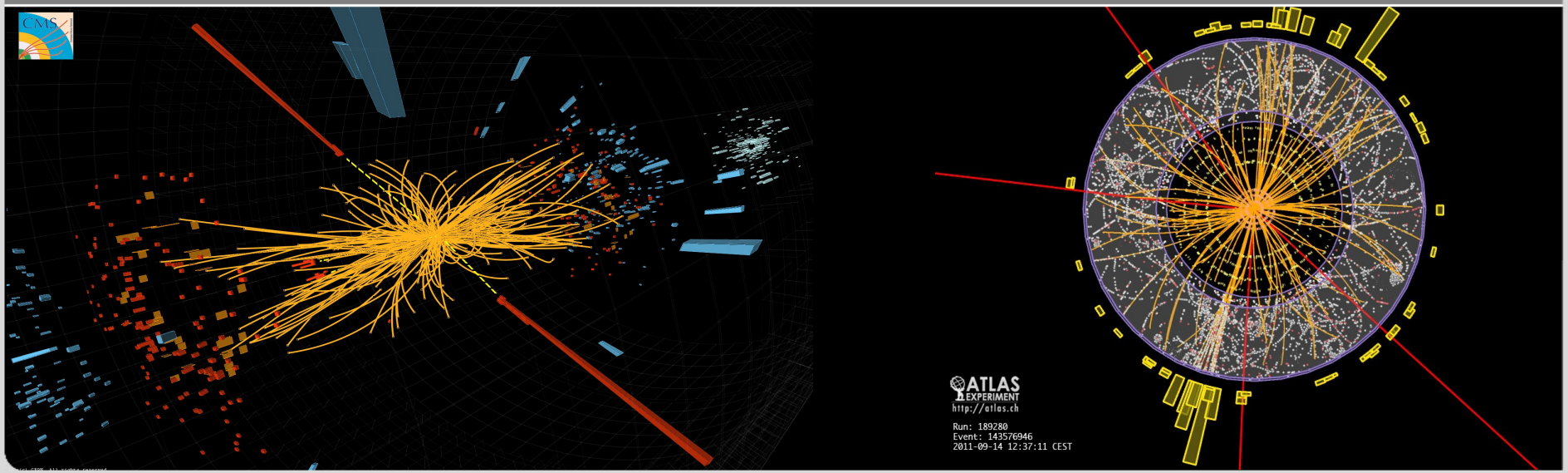
Master-Kurs
SS 2012

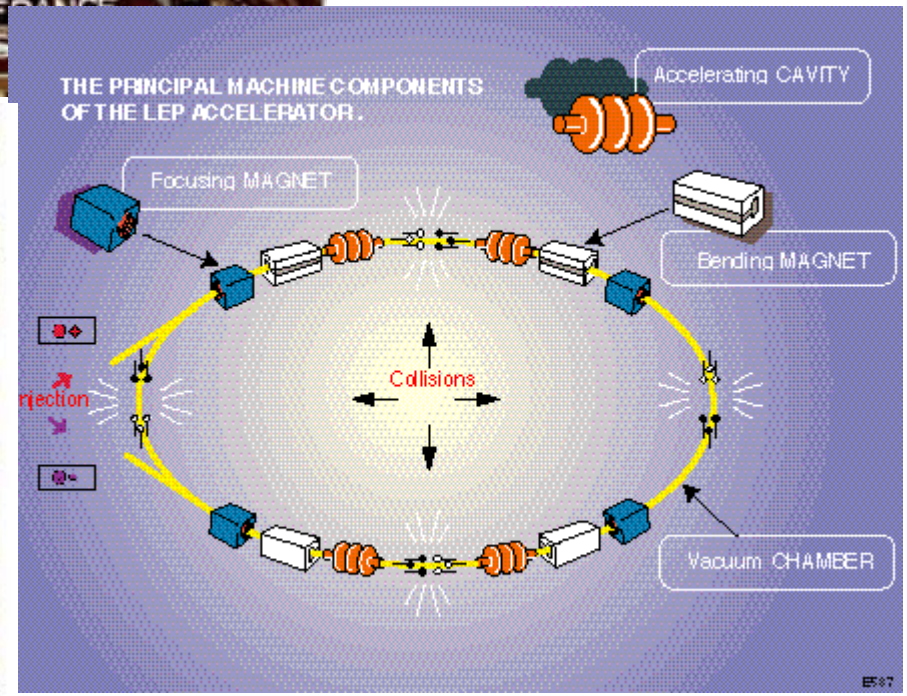
Institut für Experimentelle Kernphysik



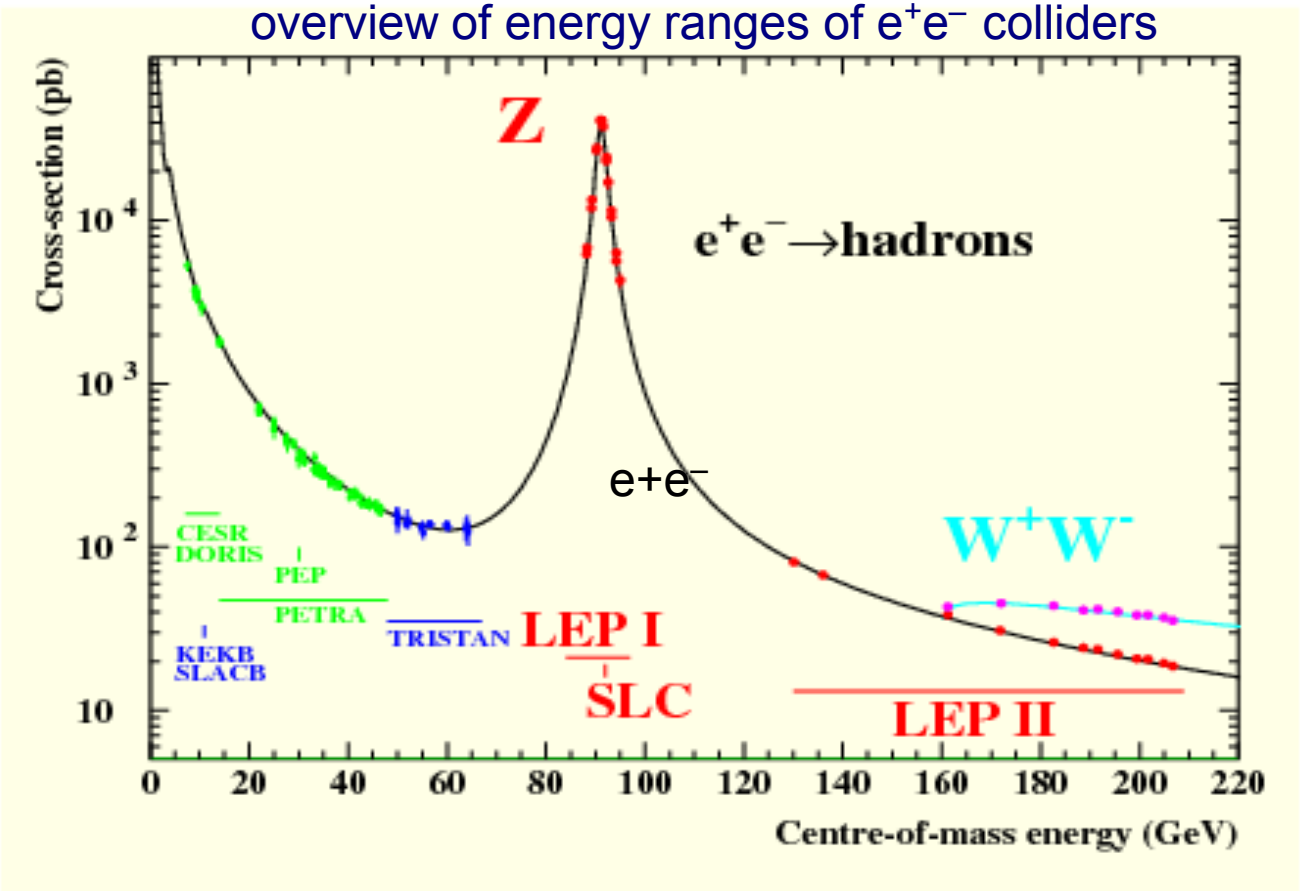
Higgs Searches @ LEP

The Large Electron Position (LEP) collider

- was in the same tunnel the LHC is in now
- operated from 1989 – 2000, the worlds largest e^+e^- machine so far
- CMS-Energies
  - ~91.2 GeV (near Z-pole) 1989 – 1995
  - 160 – 208 GeV 1996-2000 (W pair production and search for new physics)



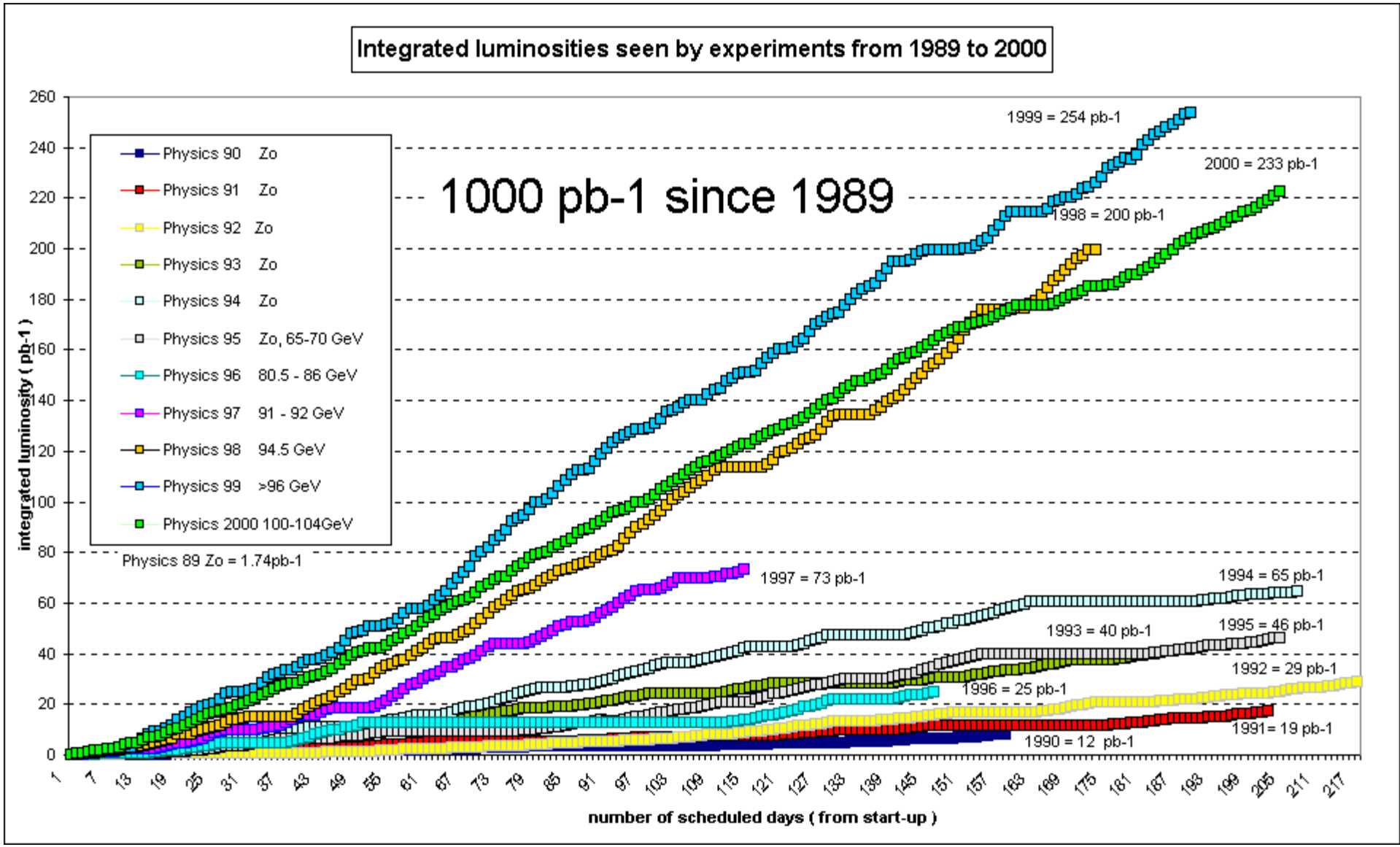
e^+e^- machines



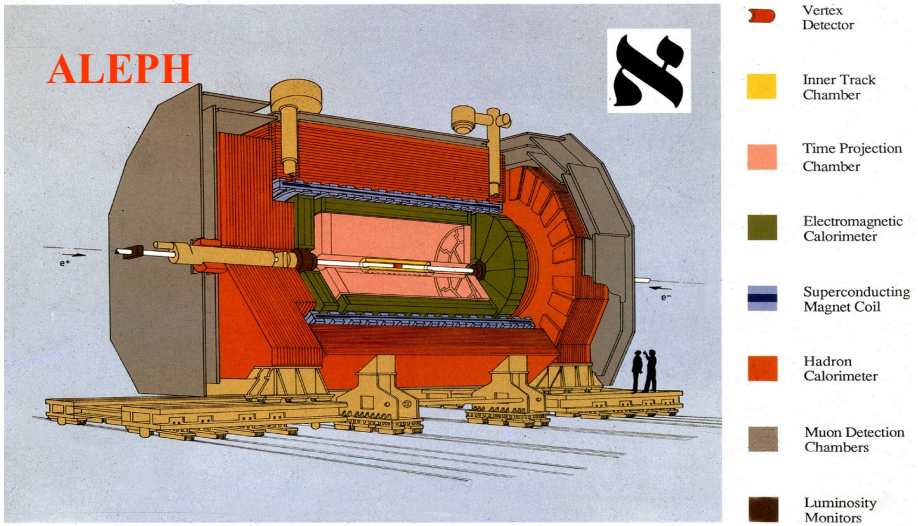
e^+e^- colliders

- provide very clean initial state
- constraint on CMS energy possible
- **maximum CMS energy limited by synchrotron radiation**

LEP – integrated luminosity per year

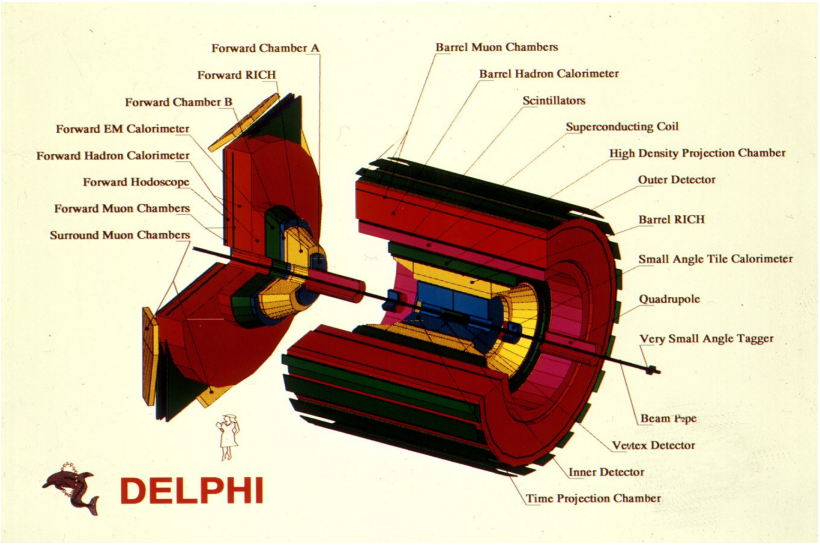


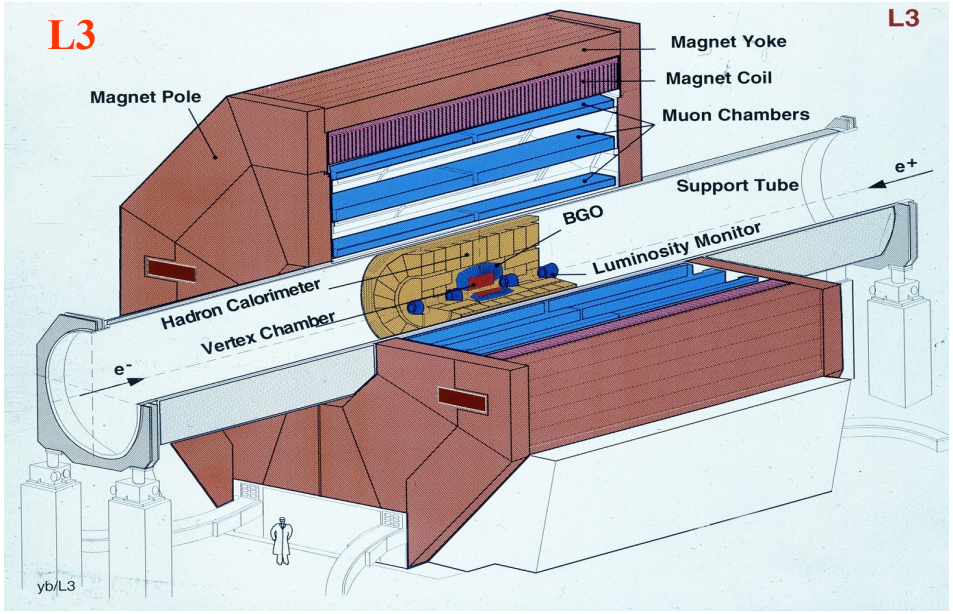
The four LEP experiments

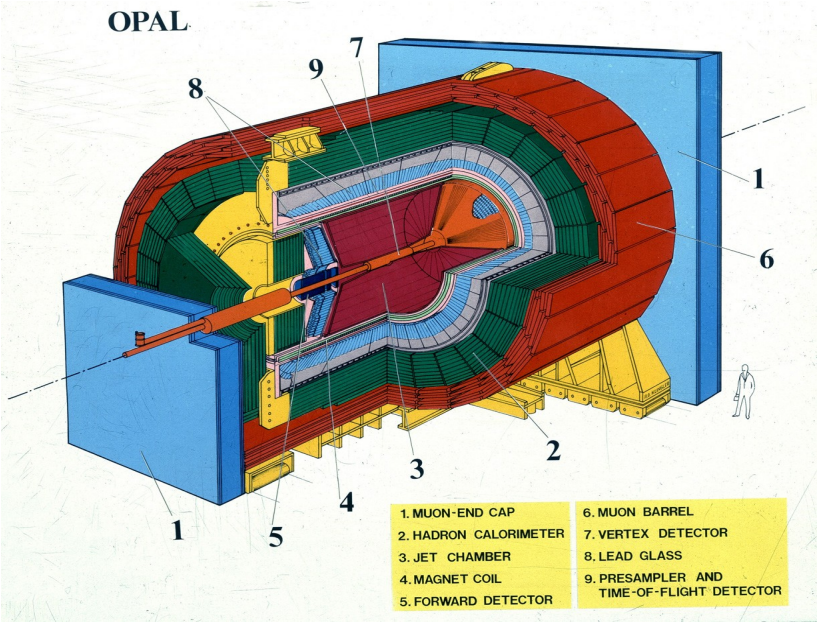


Vertex Detector
Inner Track Chamber
Time Projection Chamber
Electromagnetic Calorimeter
Superconducting Magnet Coil
Hadron Calorimeter
Muon Detection Chambers
Luminosity Monitors

Fig. 1 - The ALEPH Detector







LEP Higgs Search

all four experiments have searched for the Higgs boson, documented in nice combined paper, see
http://lephiggs.web.cern.ch/LEPHIGGS/papers/LEP-SM-HIGGS-PAPER/index.html
(published in Phys.Lett.B565:61-75,2003)

Search for the Standard Model Higgs Boson at LEP

G. Abbiendi, et al. (the ALEPH Collaboration, the DELPHI Collaboration, the L3 Collaboration and the OPAL Collaboration, The LEP Working Group for Higgs Boson Searches)

(Submitted on 16 Jun 2003)

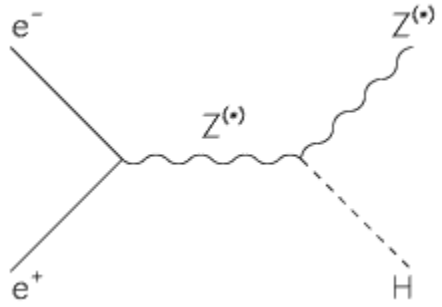
The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have collected a total of 2461 pb-1 of e+e- collision data at centre-of-mass energies between 189 and 209 GeV. The data are used to search for the Standard Model Higgs boson. The search results of the four collaborations are combined and examined 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 GeV/c2 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.

lower mass bound on Higgs mass

Higgs production in e^+e^-

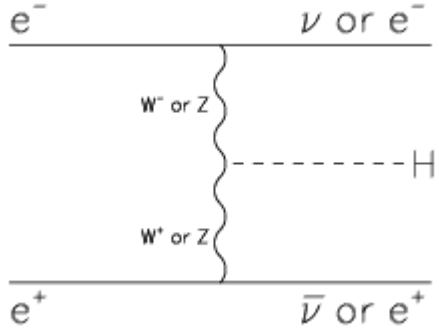
cross section ee → H far to small (small electron mass implies small Yukawa couplings)

Dominant process:



Higgs radiation from Z – Higgsstrahlung

small contribution:



WW or ZZ fusion

H and Z in final state
→ kinematic reach:
$M_H \leq \sqrt{s} - M_Z$

Higgs decays to heaviest possible particles, $b\bar{b}$ and $\tau^+\tau^-$ → Search channels @ LEP II

four fermions in final state:

$b\bar{b}q\bar{q}$	$(\sim 64\,\%)$
$H\nu\bar{\nu}$	$(\sim 20\,\%)$
$H\ell^+\ell^-$ (i.e. $e^+e^-, \mu^+\mu^-$)	$(\sim 7\,\%)$
$H\tau^+\tau^-, \tau^+\tau^- q\bar{q}$	$(\sim 9\,\%)$

Cross sections @ LEP

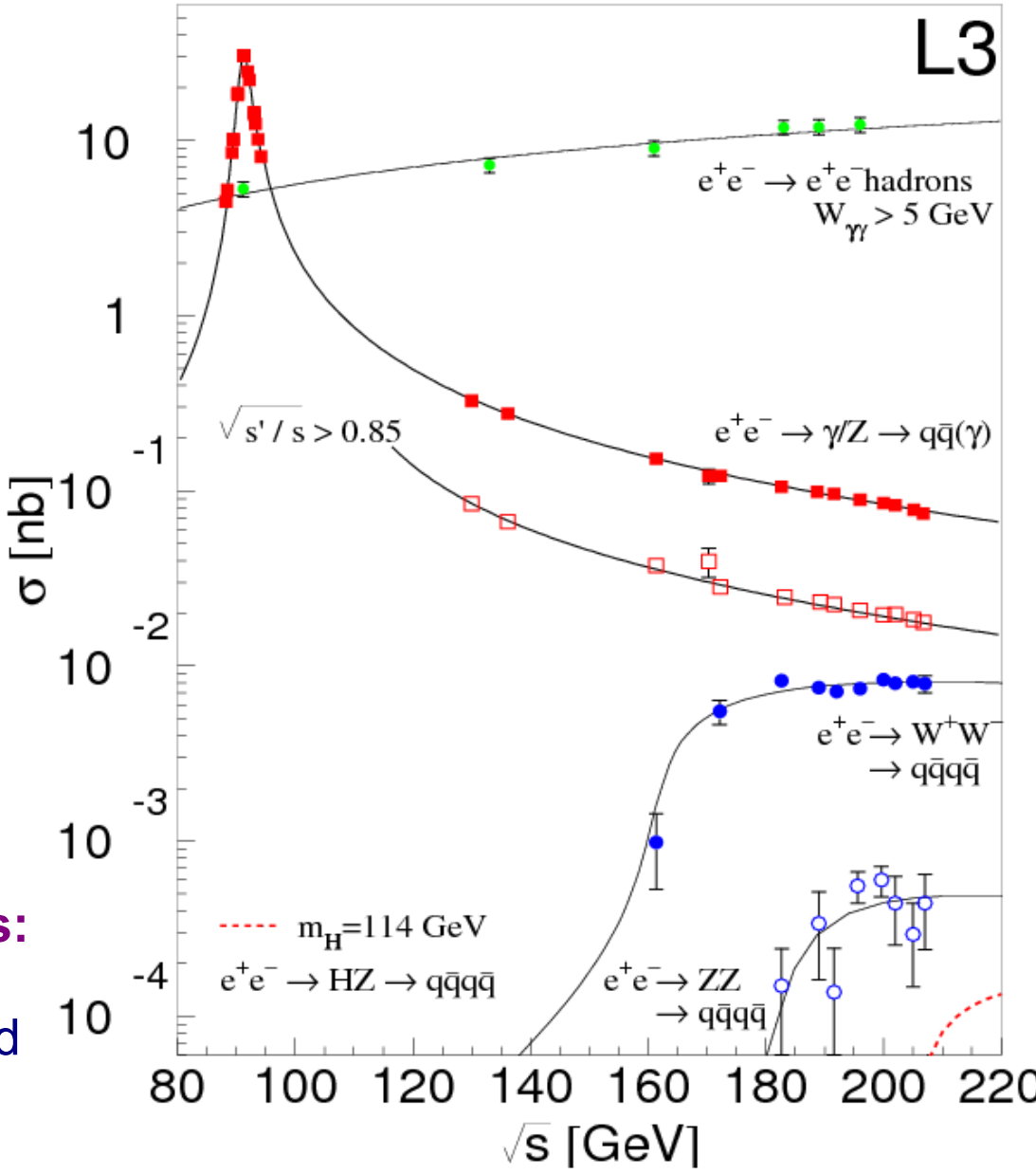
Higgs production cross section
is very small

→ selective search for a signal
on top of a huge background

Advantage @ LEP:
backgrounds well understood
theoretically;

dominant background:
– Z decays for H mass near Z-Pole;
– ZZ production at higher mass

important experimental features:
excellent b- and tau- tagging
and resolution of reconstructed
mass of Higgs candidates



Analysis details

Higgs analyses are performed in bins of
- reconstructed Higgs mass m_H^{rec}
- and a discriminating variable $\mathcal{G}$ (combining many experimental features like b-tagging variables, likelihood or neural network outputs)

Experiments provide
- number of expected background events
- number of expected signal events
- number of observed events in data

for each bin in (m_H^{rec} , $\mathcal{G}$)

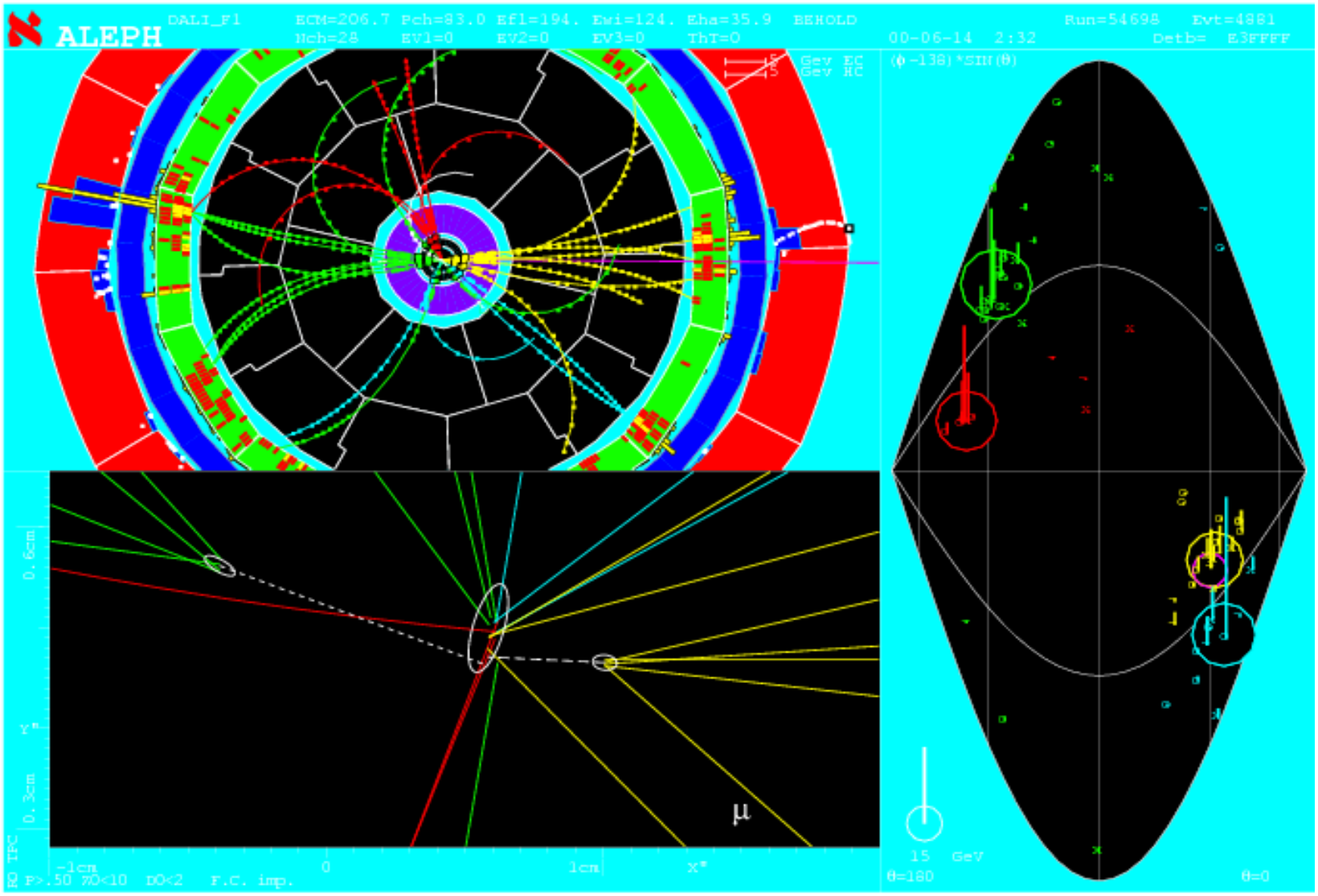
interpolations are performed
for statistical analysis at any given Higgs mass

Limit setting based on Likelihood ratio $Q = \frac{\mathcal{L}_{S+B}}{\mathcal{L}_B}$ of signal-plus-background and background-only hypotheses

more convenient: use $2 \ln Q$ instead, as this can be interpreted like a difference in χ^2 of the S+B and the B hypotheses;
furthermore, it can be constructed from the sum of contributions of individual observed events.

Higgs candidats @ LEP

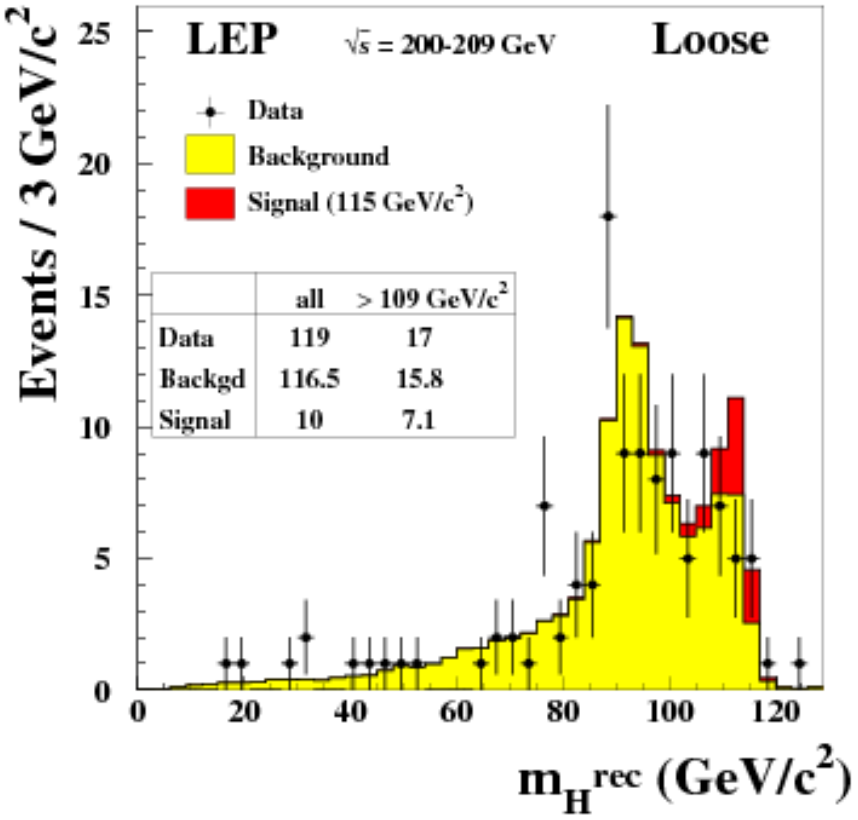
Candidates were observed: $b\bar{b}q\bar{q}$ event in ALEPH ...

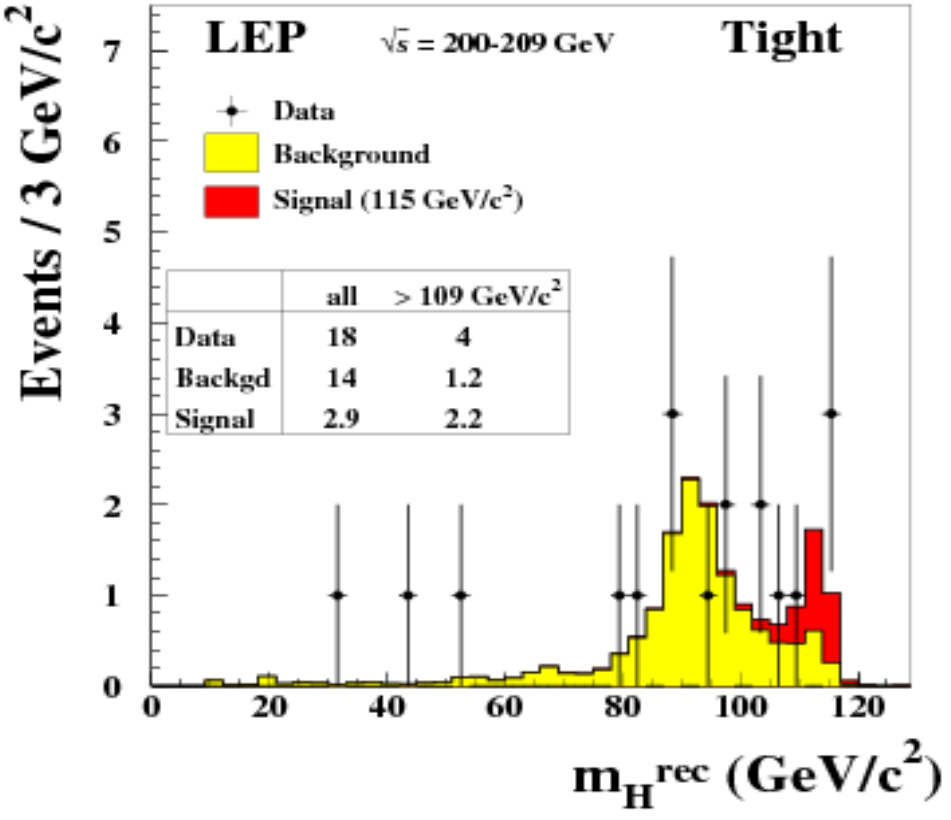


… could also be ZZ*

Results of LEP Higgs search

distributions of reconstructed Higg boson mass loose and thight selections



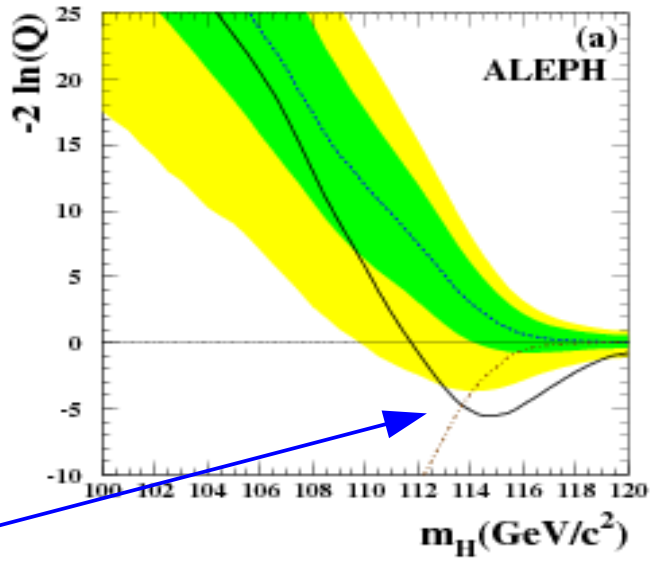


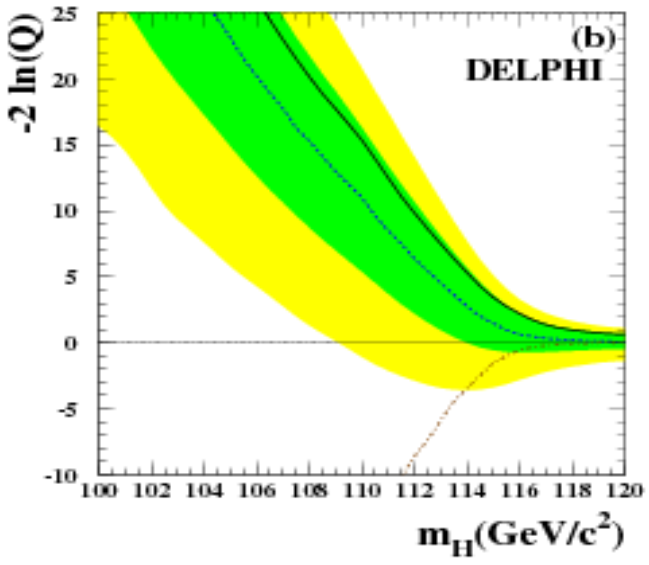
– only very small number of signal events expected
– slight, but not significant excess seen (most events in only one experiment)

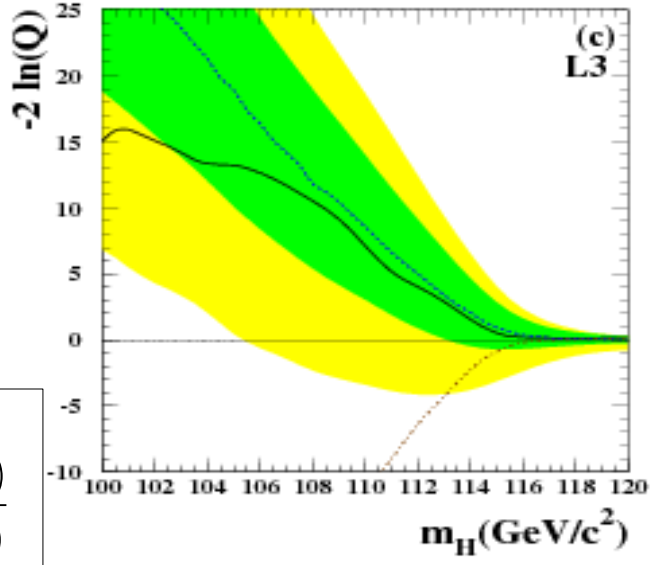
Results in 2lnQ

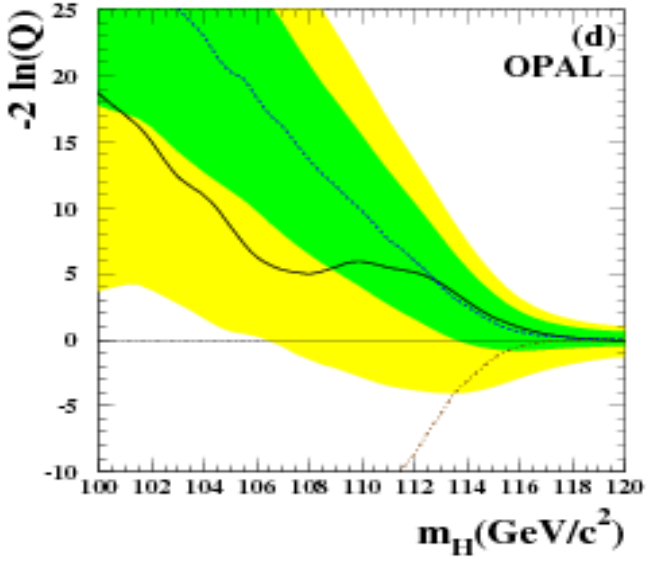
--- expected
for background
--- expected
for signal
black line:
observed -2lnQ

slight signal-like excess from three events in ALEPH only.







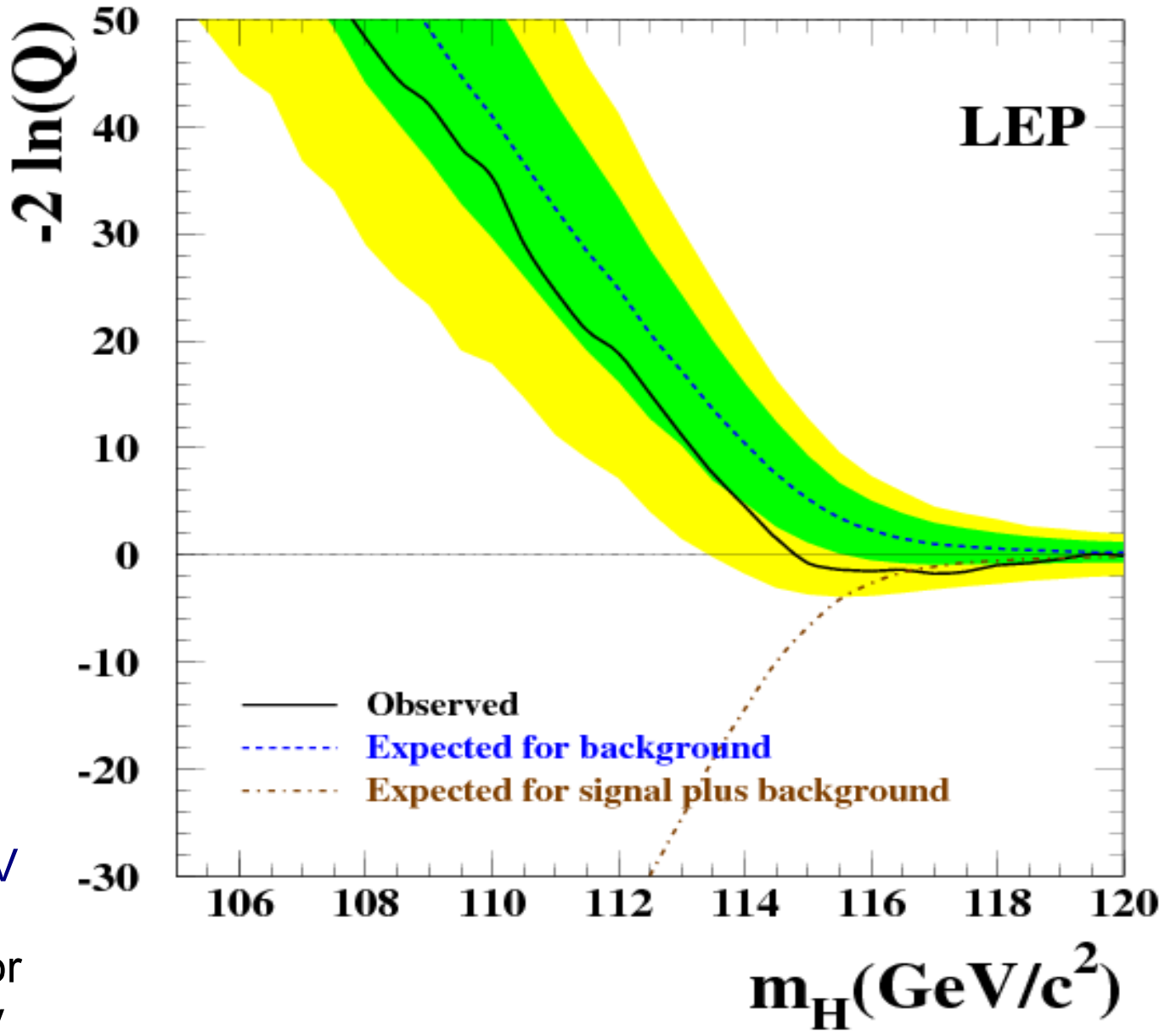


reminder:

$$-2\ln Q = -2\ln\frac{\mathcal{L}(data|\mu,\tilde{\Theta})}{\mathcal{L}(data|0,\tilde{\Theta})}$$

likekihood ratio used at LEP

Result in 2lnQ for LEP combined



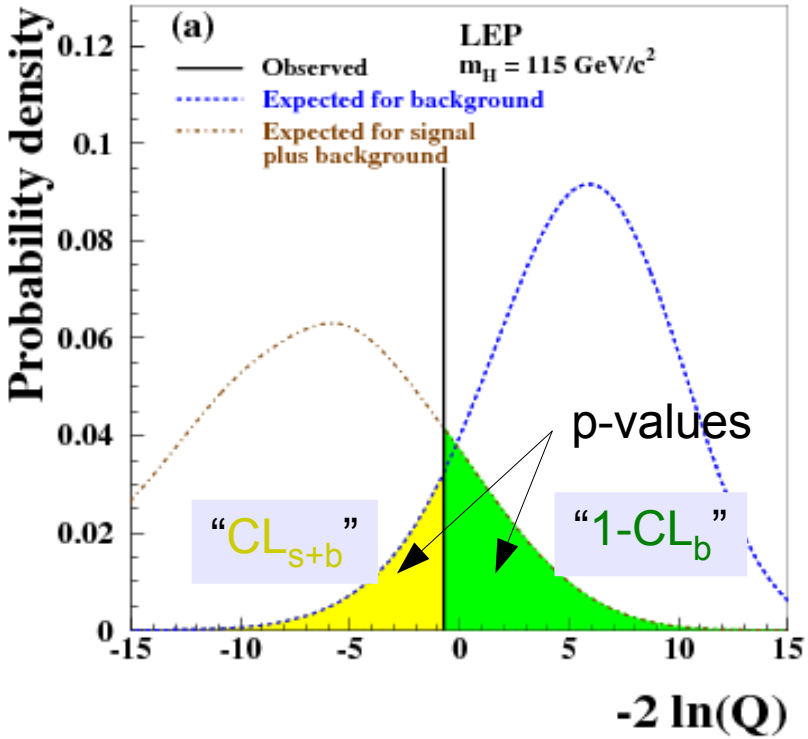
observed -2lnQ
at ~114-118 GeV
more signal-like
than expected for
background only

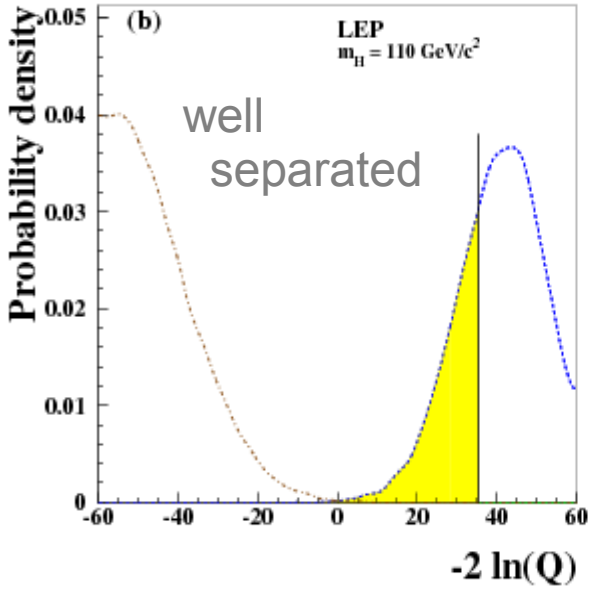
Probability densities for S+B and B-only

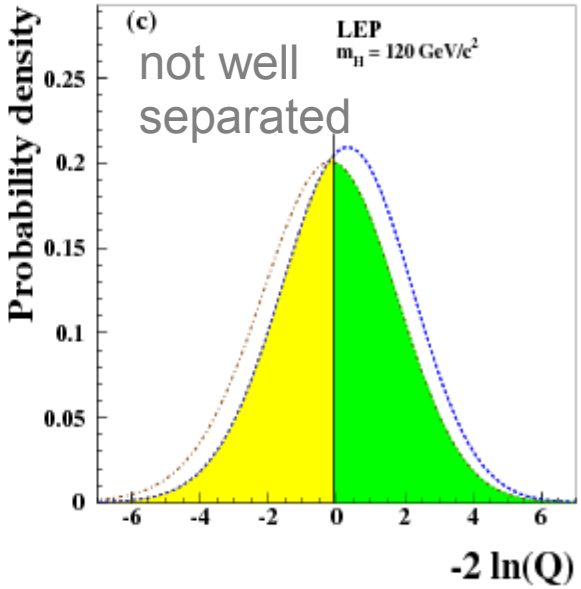
as a consequence:

set limits

need **distribution of teststatistic –2lnQ** under S+B and B-only hypotheses







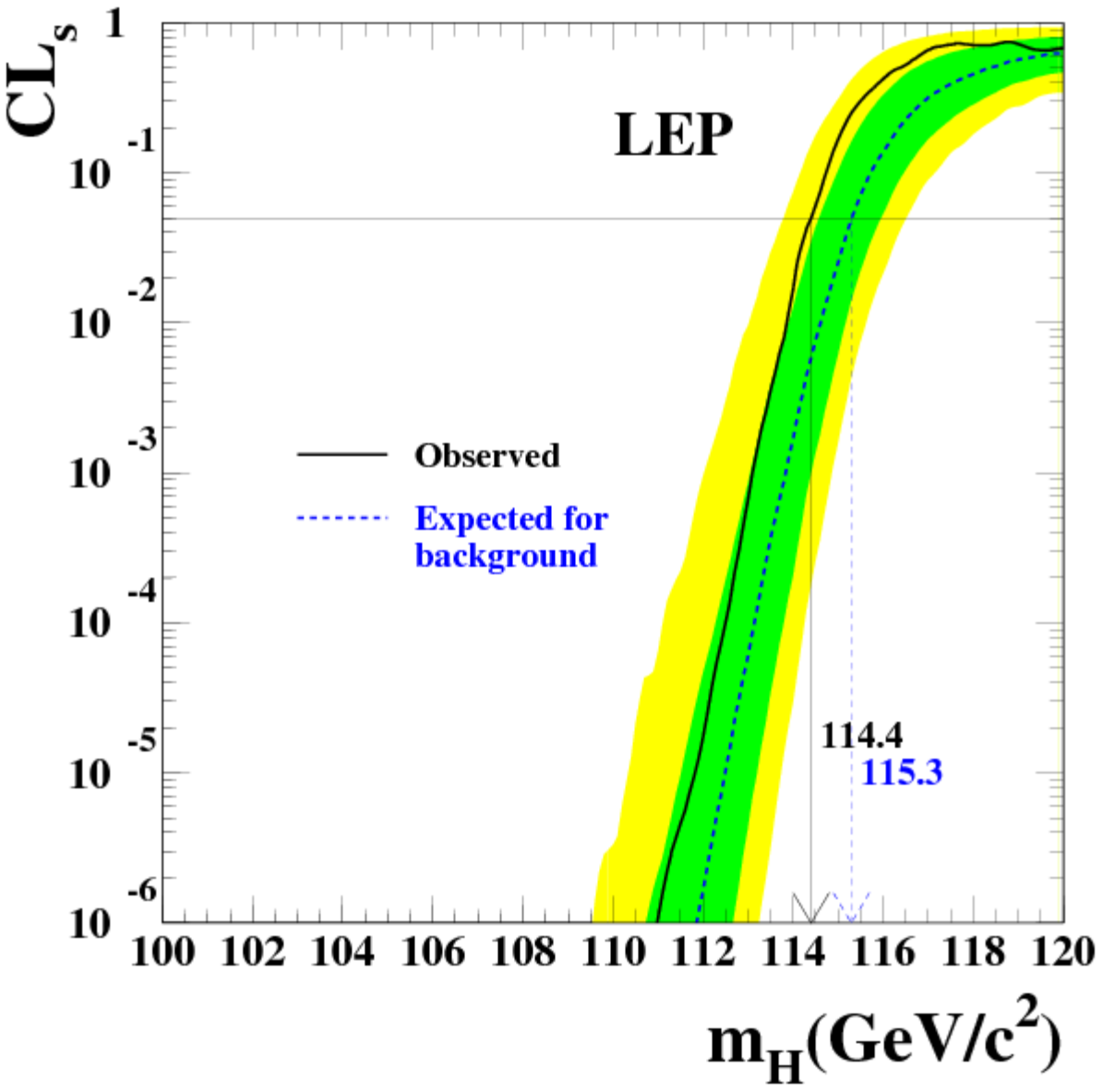
Limit setting based on "CLs"

Use robust
"**CL_s**" – method,

$$CL_s = \frac{CL_{s+b}}{1 - CL_b} \ ,$$

to set limit

m_H>114,4 GeV/c^2

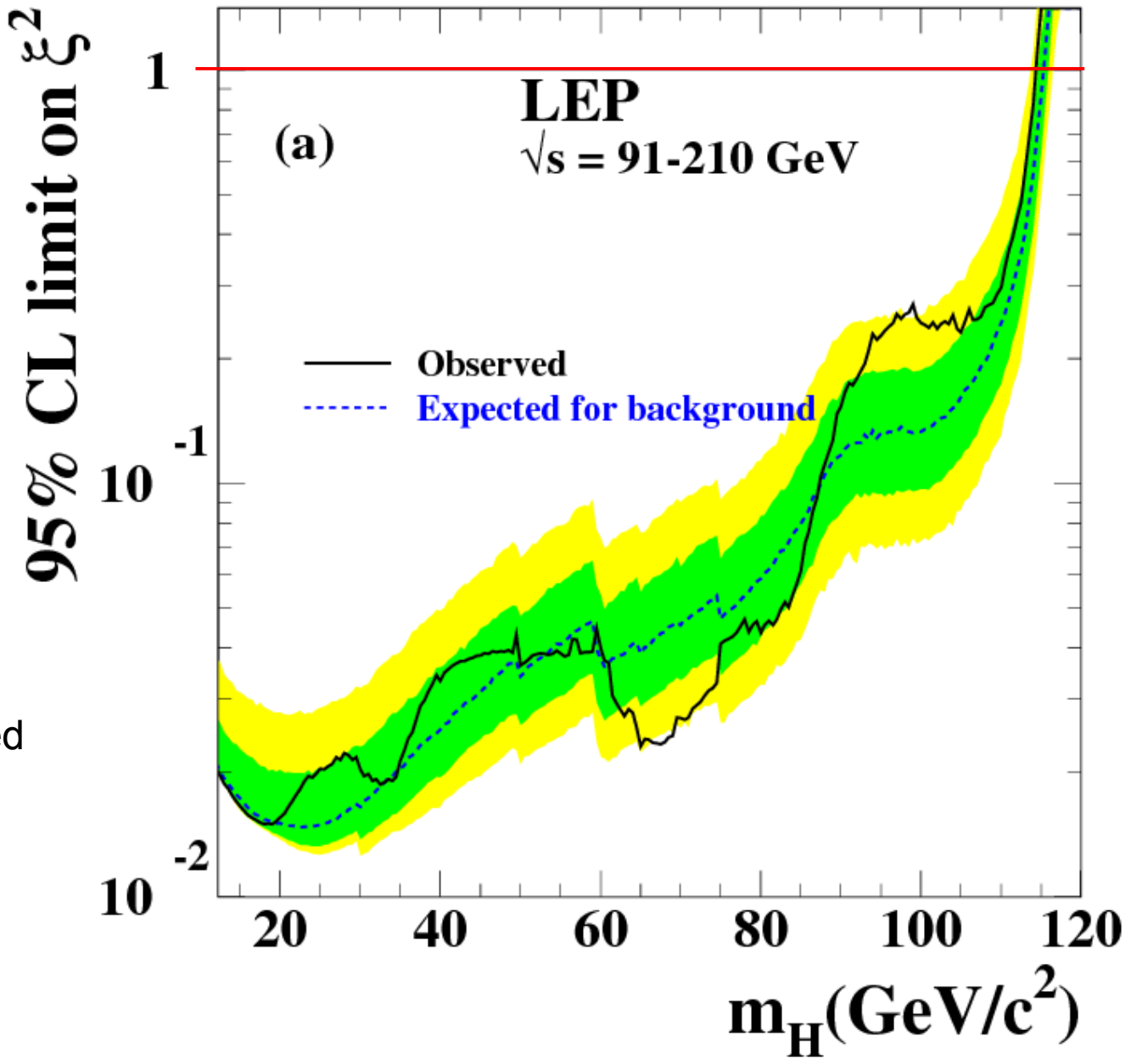


displayed differently ...

95% CLs - limit

on Higgs production cross section relative to SM expectation

$$\xi^2 = \frac{{g_{HZZ}}^2}{{g_{HZZ}^{(SM)}}^2} = \frac{\sigma_{HZZ}}{\sigma_{HZZ}^{(SM)}}$$



$\xi^2 < 1$: SM Higgs excluded

$\xi^2 > 1$: SM Higgs cannot be excluded

Higgs search @ LEP

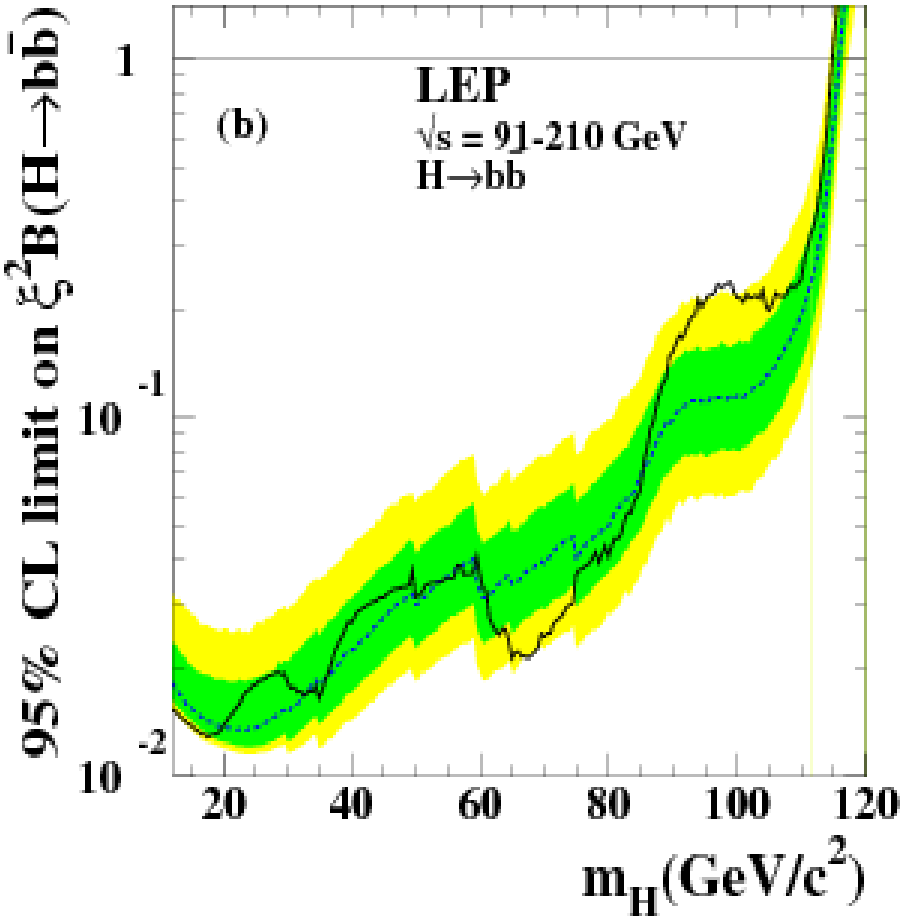
Exclusion of light SM Higgs boson

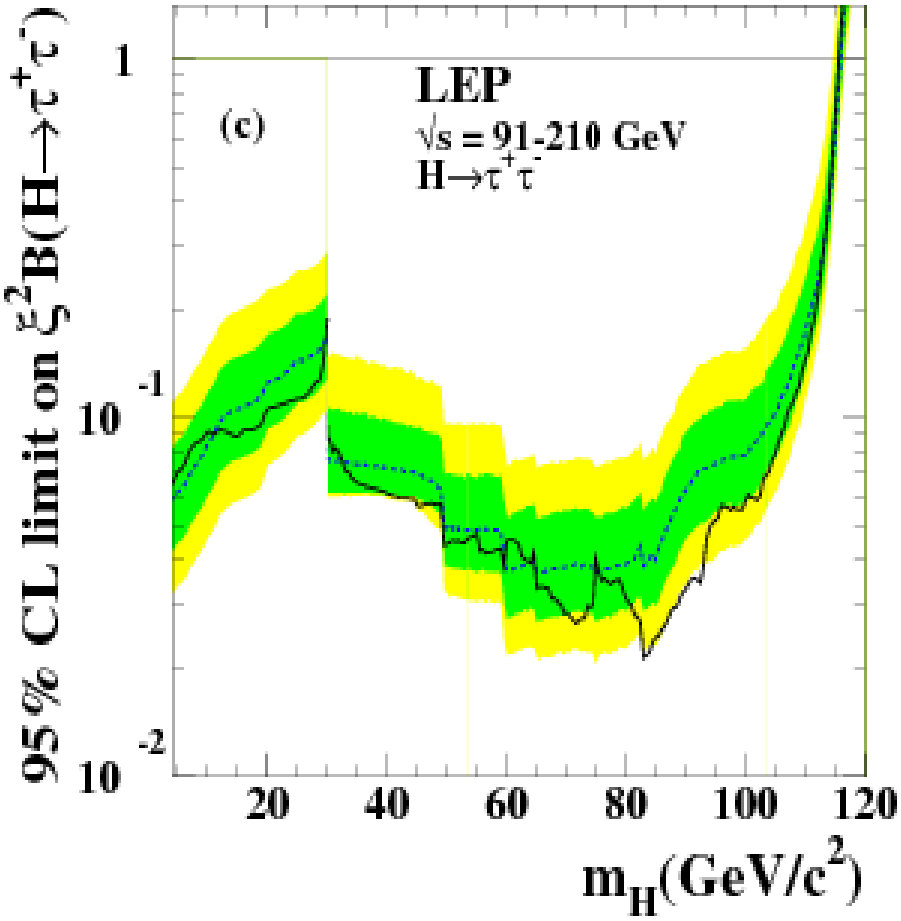
limit expected: $M_H > 115{,}3$ GeV/c^2

observed: $M_H > 114{,}4$ GeV/c^2

Aleph, Dephi, L3, OPAL, data up to 2000, publ. 25/4/2003

ξ^2 for $H \to b\bar{b}$ and $H \to \tau^+\tau^-$ separately





(steps due to changed analyses for different mass ranges)

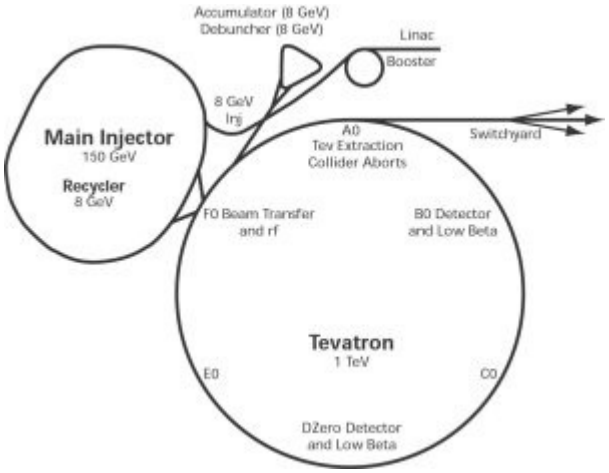
Sorry, Mr. Higgs, ask the Tevatron

Message on LEP status screen
after last run on Nov. 2nd 2000,
following a 6 week run extension

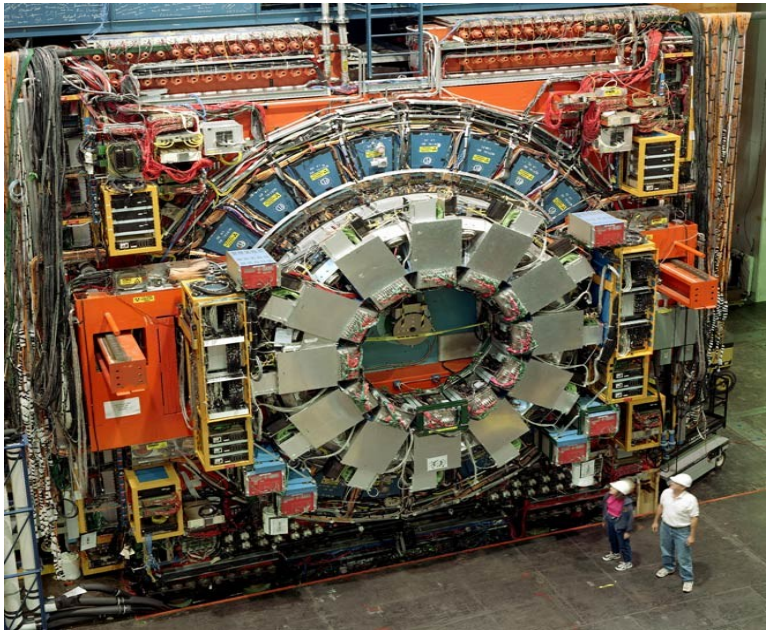
Higgs Searches @ Tevatron

Tevatron $p\bar{p}$ Collider

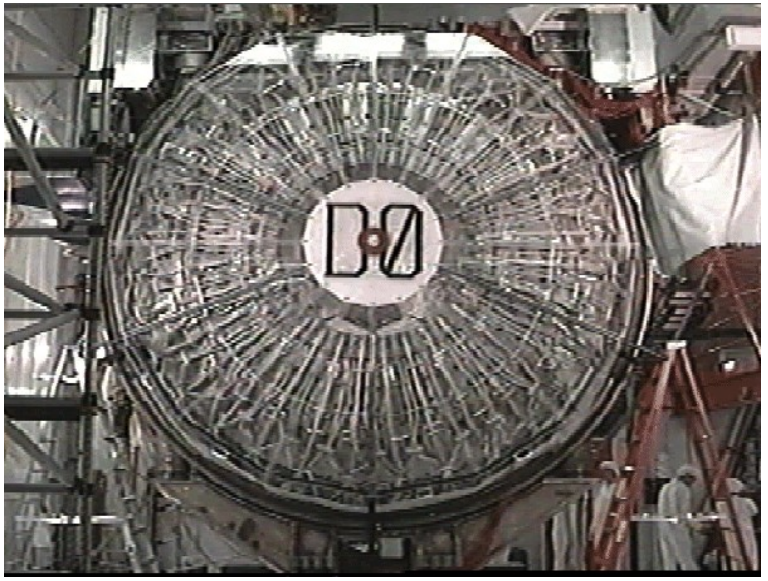
Tevatron $p\bar{p}$ Collider



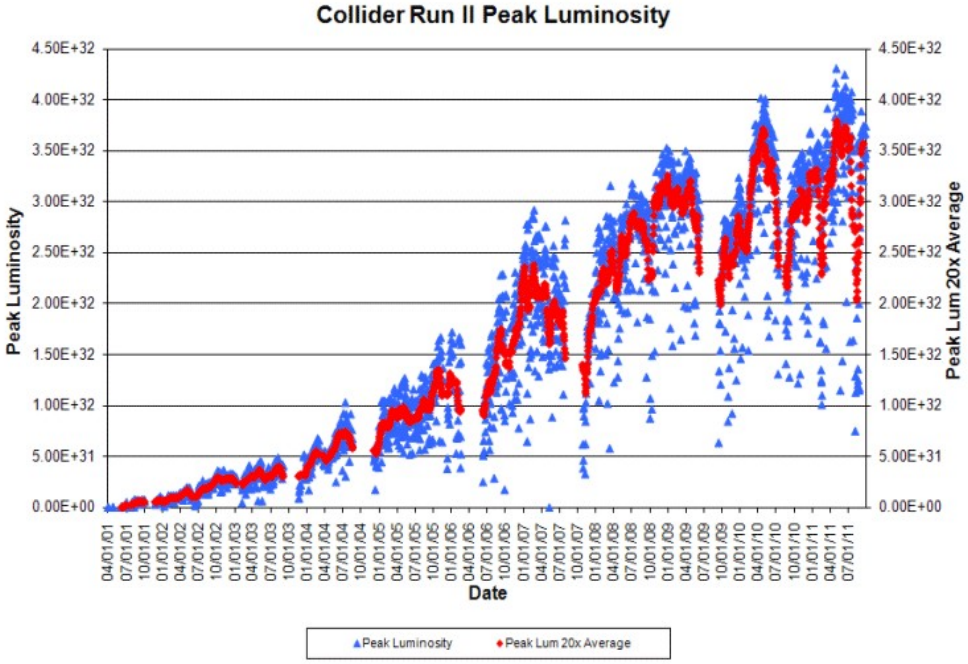
CDF experiment



D0 experiment



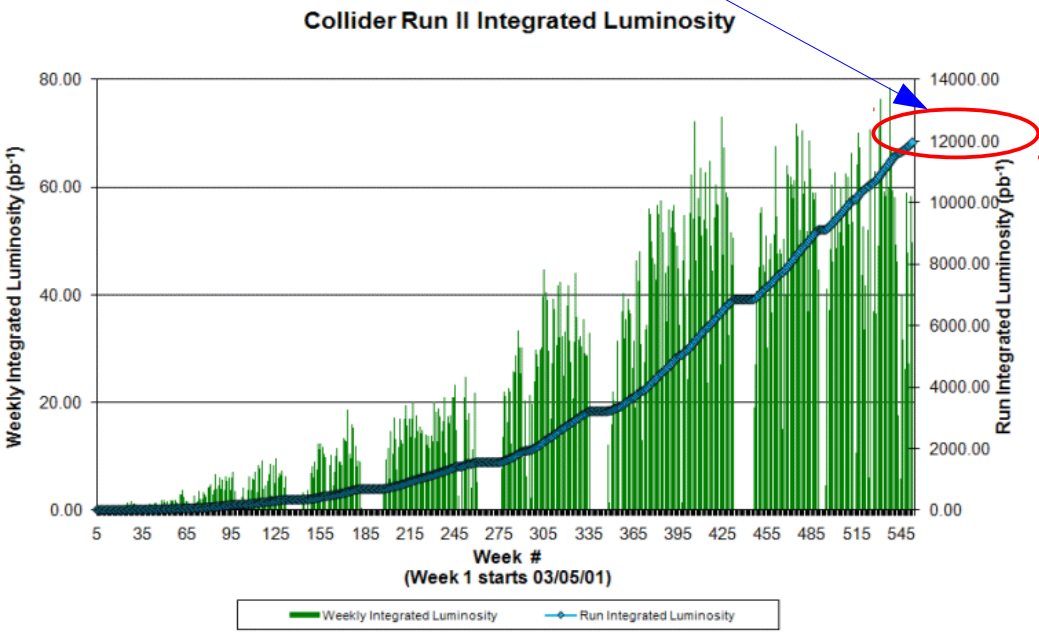
Collider performance



peak luminosity constantly improved

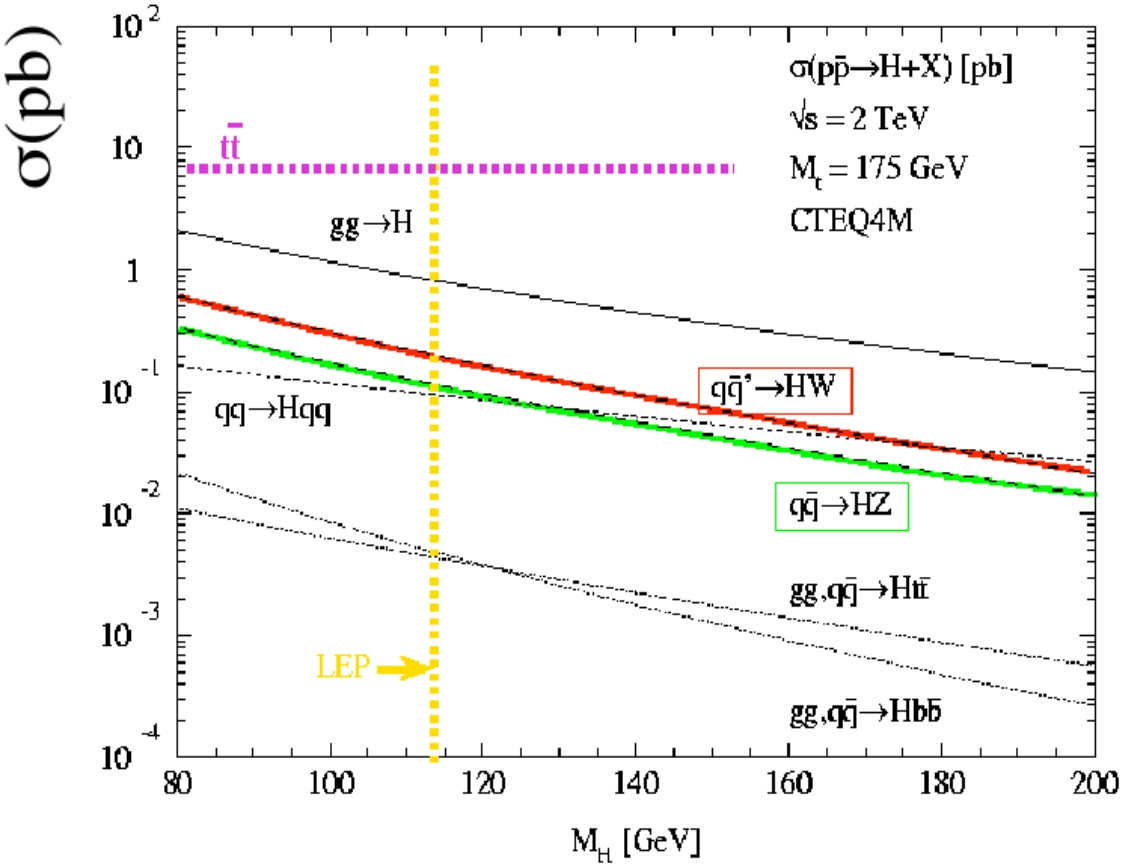
Tevatron ran at 2 TeV c.m.s energy from 2001 – 2011
"Tevatron Run II"

∫L of 12/fb delivered to experiments CDF and D0

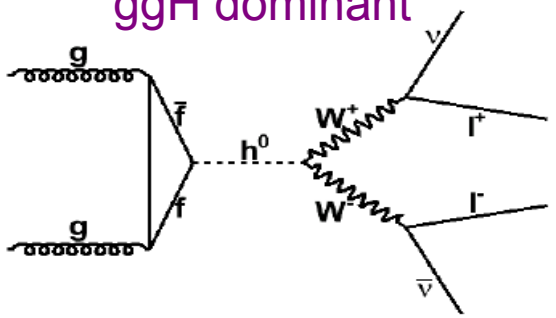


Data taking efficiency of experiments typically ~90%
→ **11/fb analysable data**

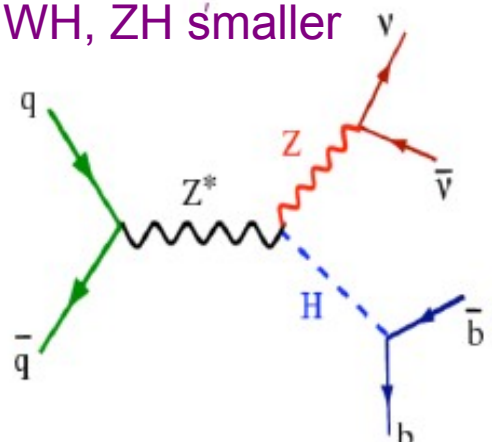
Higgs production at 2 TeV

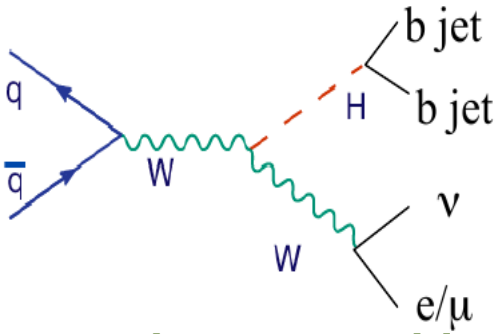


ggH dominant



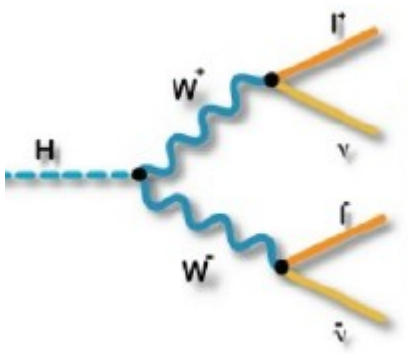
WH, ZH smaller





vector boson provides additional signature

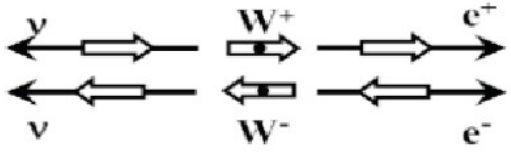
H → WW at Tevatron

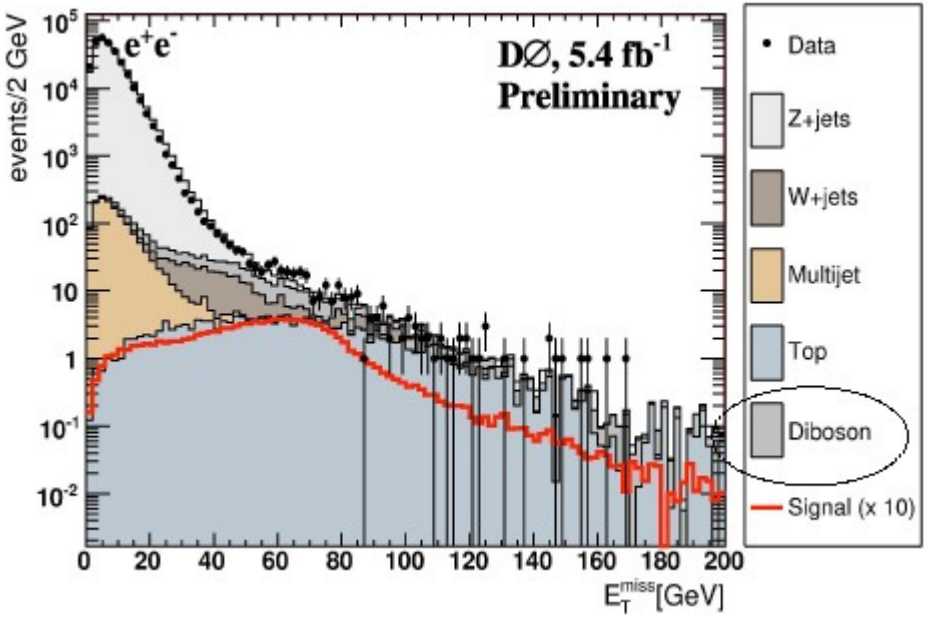


signature:

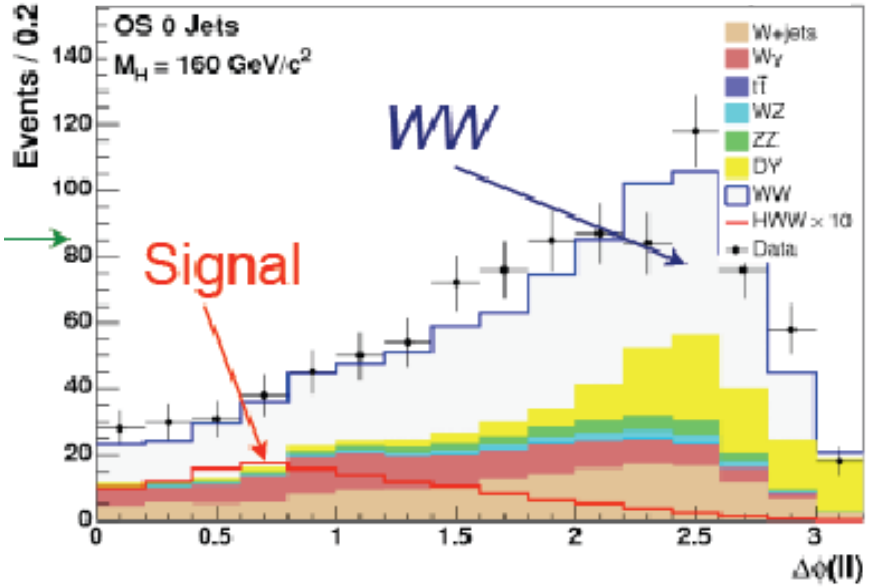
– two isolated, opposite-charge leptons
– large missing transverse momentum / energy

exploit pin correlation)



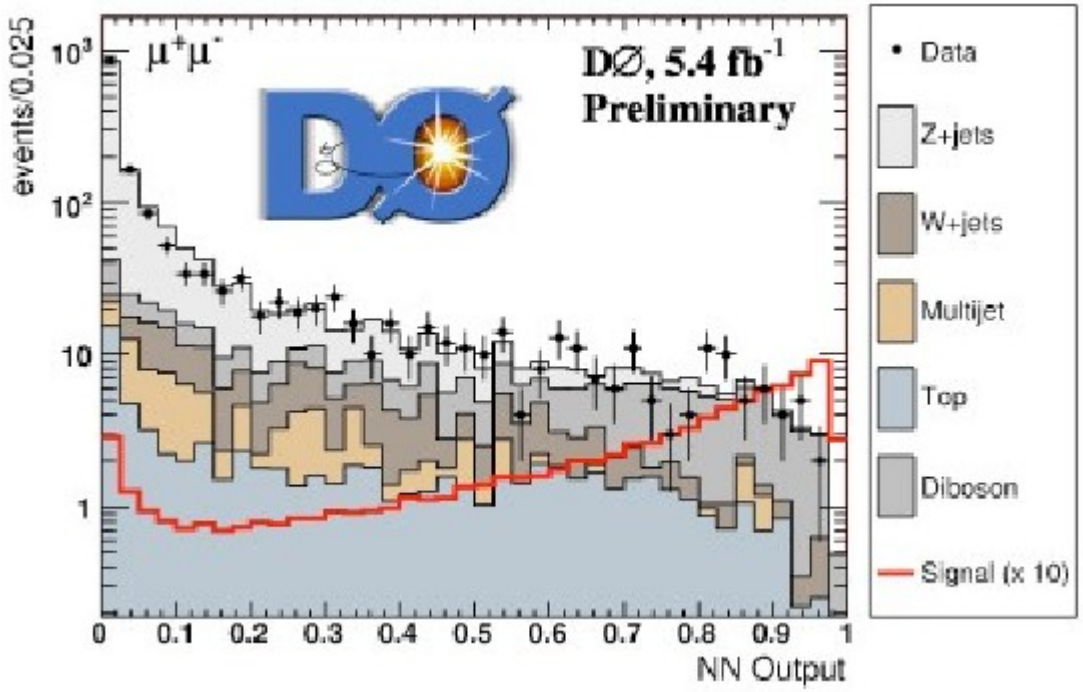


CDF 4.8 / fb



→ cut on angle between leptons suppresses irreducible WW background

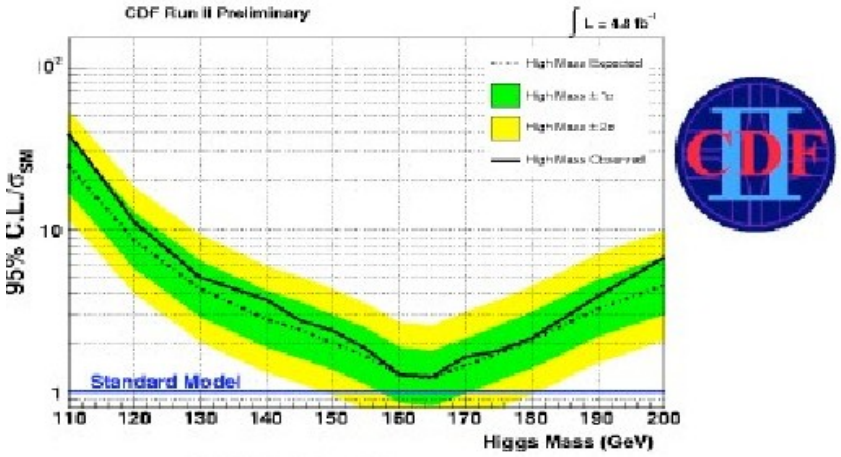
H → WW at Tevatron



combining many variables using an artificial neural network gives sensitivity to Higgs signature.

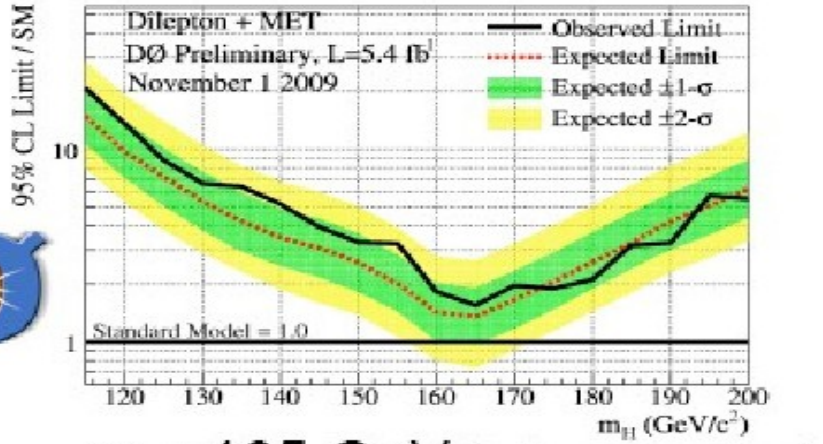
In 2009, CDF and D0 were just about reaching sensitivity to a SM Higgs boson with mas around 160 GeV

~30 signal events per experiment expected in final selection



m_H=165 GeV

Exp/Obs: 1.21/1.23 x σ_{SM}

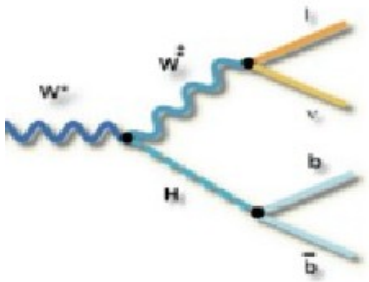


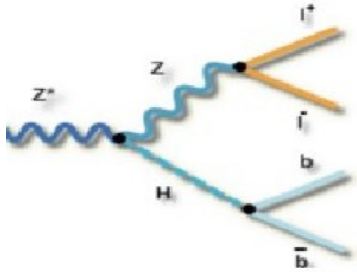
m_H=165 GeV (w/o same sign)

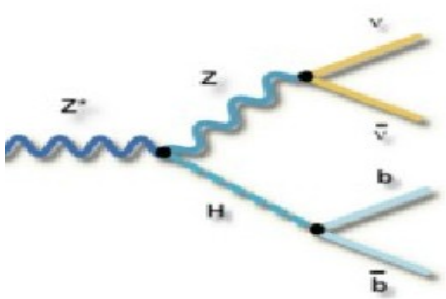
Exp/Obs: 1.36/1.55 x σ_{SM}

H → $b\bar{b}$ at Tevatron

need addional object(s) to trigger H→$b\bar{b}$ events:

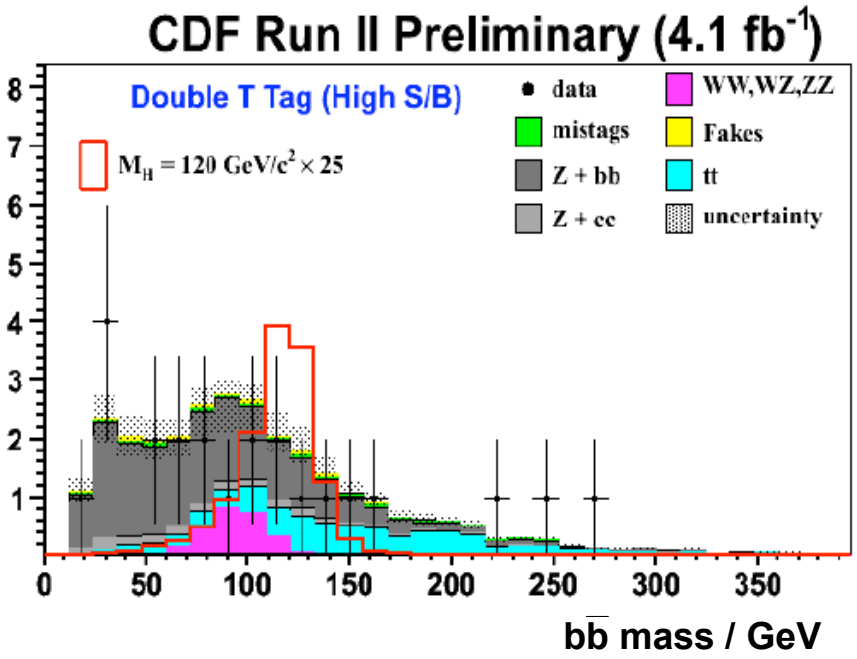


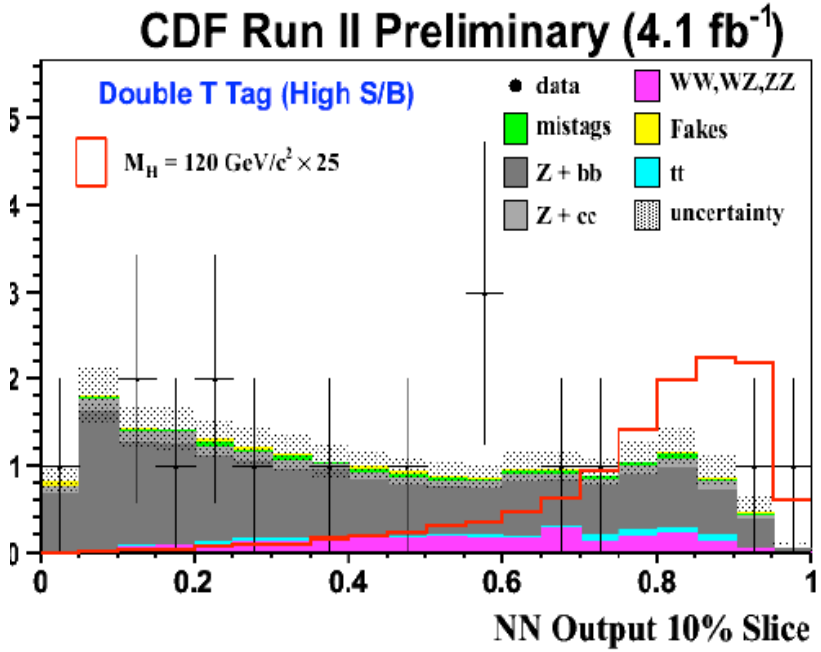




signatures:

$b\bar{b}$+missing E_T+lepton	$b\bar{b}$+2 leptons	$b\bar{b}$+missing E_T
large σ	low BG	large Z Br.
large background	small σ*BR	large BG





Very difficult analysis

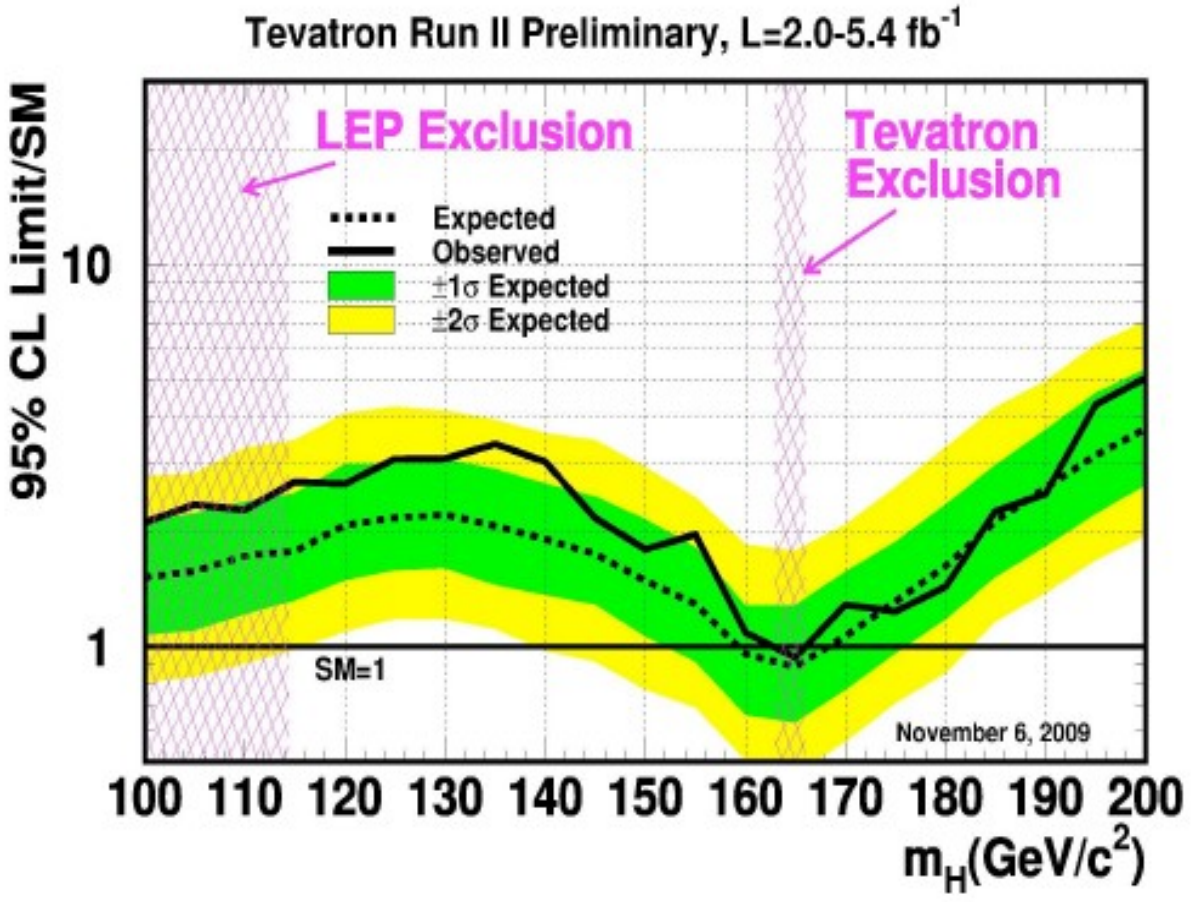
Testatistic: likelihhod rato (similar to LEP)

$$"LLR" = -2\ln Q = -2\ln \frac{\mathcal{L}(data|\mu,\hat{\Theta})}{\mathcal{L}(data|0,\hat{\Theta})}$$

likekihood ratio used at teststatistic at Tevatron

almost identical to LEP, except that profiling of likelihood is done for nuisance parameters ($\hat{\Theta}$) instead of using pre-determined values ($\tilde{\Theta}$)

Tevatron Higgs Exclusion 2009



For the first time after LEP II, Tevatron excluded an additional small range around 160 GeV/c^2 in Higgs mass

Higgs search @ Tevatron

reached sensitivity to SM Higgs only recently near WW threshold.

vast number of channels analyzed and combined:

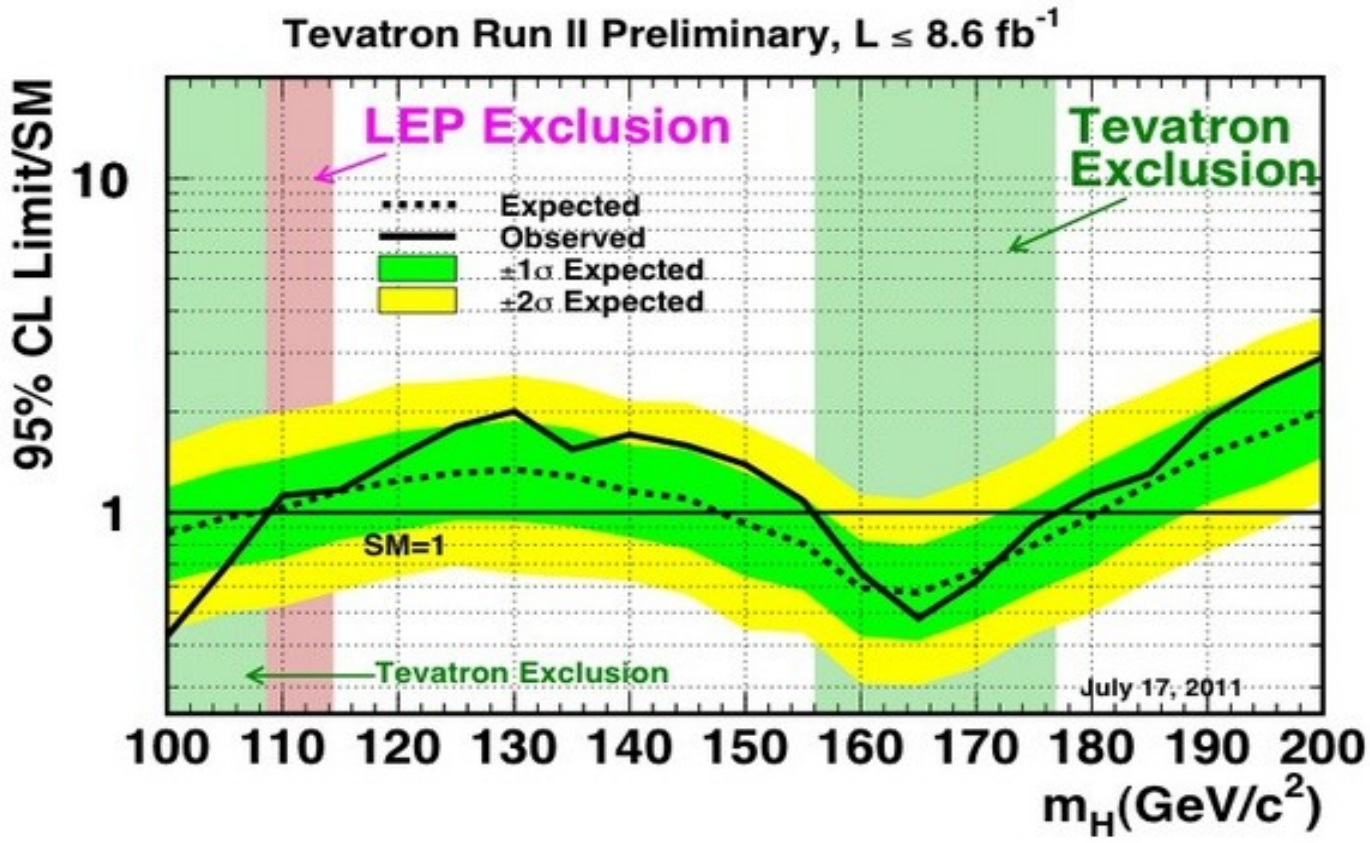
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(TT,TL,Tx,LL,Lx)	9.45	100-150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(TT,TL)	9.45	100-150
$ZH \to \nu\bar{\nu}b\bar{b}$ (SS,SJ,1S)	9.45	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(TT,TL,Tx,LL)	9.45	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(TT,TL,Tx,LL)	9.45	100-150
$H \to W^+W^-$ 2×(0 jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$)	9.7	110-200
$H \to W^+W^-$ (e-τ_{had})+(μ-τ_{had})	9.7	130-200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	9.7	110-200
$WH \to WW^+W^-$ tri-leptons with 1 τ_{had}	9.7	130-200
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)	9.7	110-200
$H \to ZZ$ four leptons	9.7	120-200
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	8.3	100-150
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ℓ-τ_{had}-τ_{had}	6.2	100-150
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ (ℓ-ℓ-τ_{had})+(e-μ-τ_{had})	6.2	100-125
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ℓ-ℓ-ℓ	6.2	100-105
$ZH \to \ell^+\ell^-\tau^+\tau^-$ four leptons including τ_{had} candidates	6.2	100-115
$WH + ZH \to jjb\bar{b}$ (SS,SJ)	9.45	100-150
$H \to \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv)	10.0	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (lepton) (4jet,5jet,≥6jet)×(SSS,SSJ,SJJ,SS,SJ)	9.45	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (no lepton) (low met,high met)×(2 tags,3 or more tags)	5.7	100-150

channels considered in CDF Higgs search
(from FERMILAB-CONF-12-065-E. March 2012)

Higgs search at Tevatron – results Sep. 2012

Tevatron running ended in autumn 2011

after analysis of ⅔ of total data (~ 8.5/fb)

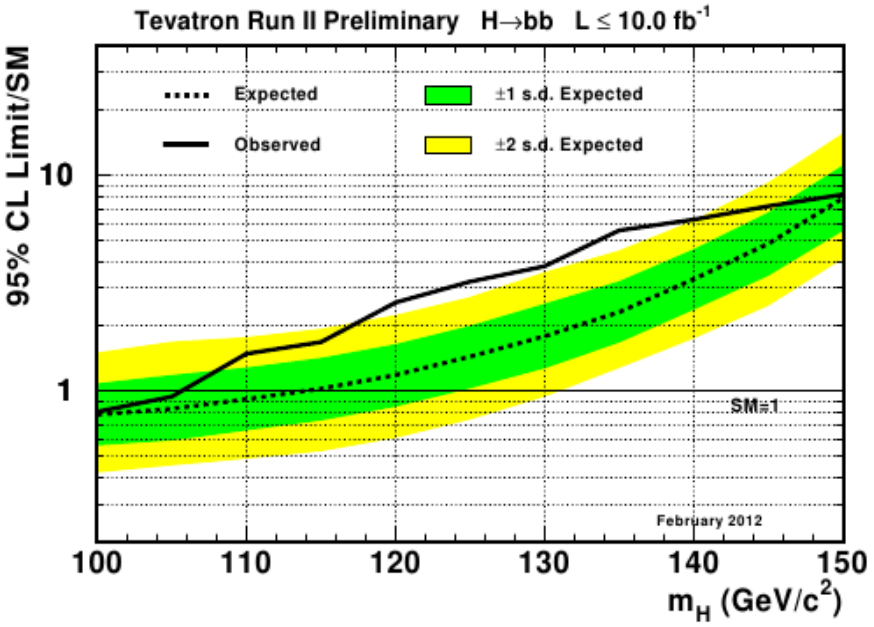


Exclusion expected: : $148 < M_H < 180$ GeV/c^2

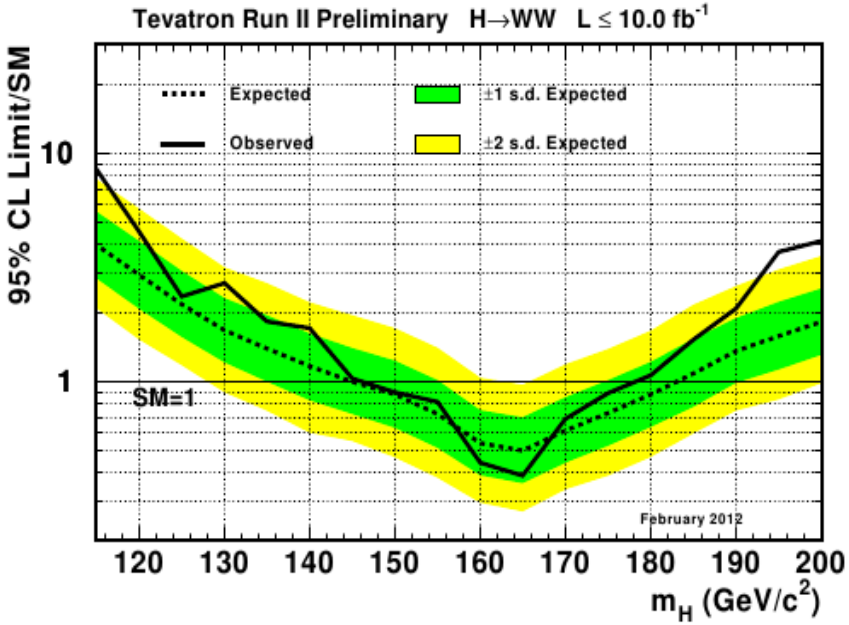
observed: $156 < M_H < 177$ GeV/c^2 (**CDF** & **D0**, Sept. 2011)

Tevatron Higgs Search – results Spring 2012

more data have been analyzed ….

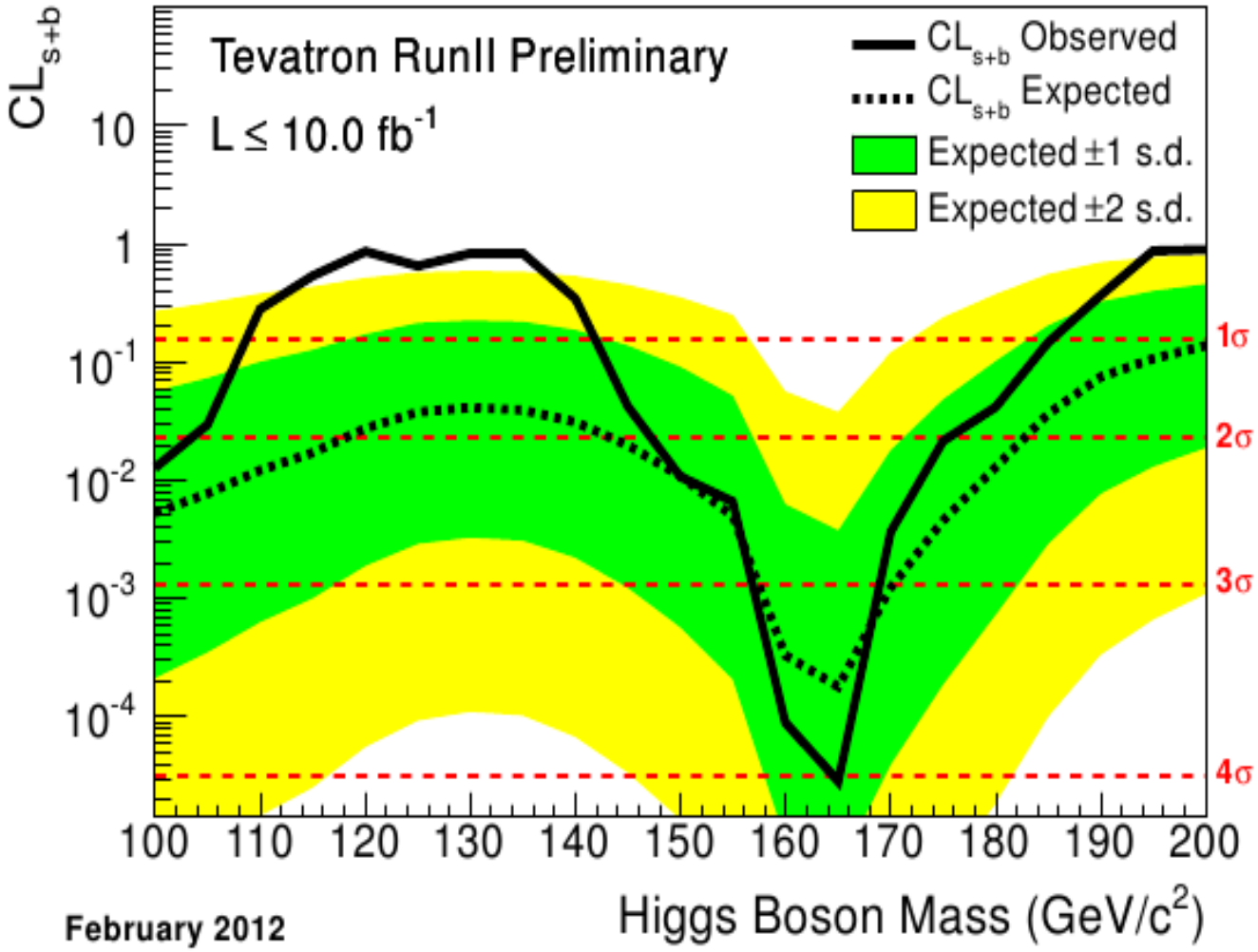


$H \rightarrow b\bar{b}$



$H \rightarrow WW$

Tevatron Higgs Search – results Spring 2012

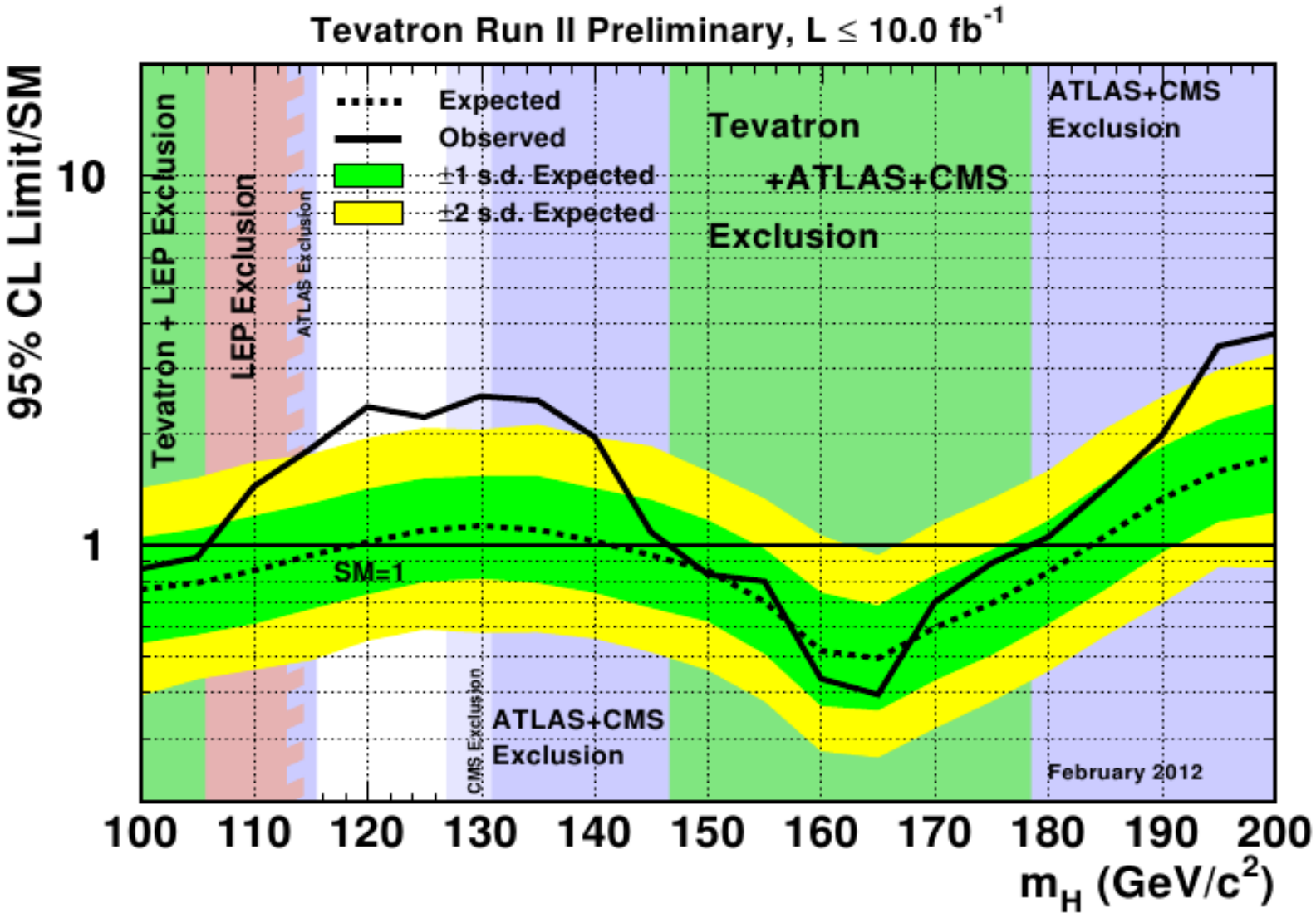


all channels combined

observe – excluded range 147 – 179 GeV/c^2

– small signal-like excess at lower mass (115 - 135 GeV/c^2)

Higgs Search → spring 2012



Tevatron competing with LHC in 2011

→ next lecture

Backup material

Production cross sections and decay branching fractions assumed for the Tevatron Higgs combination

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$\sigma_{t\bar{t}H}$ (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to\gamma\gamma)$ (%)
100	1821.8	281.1	162.7	97.3	8.0	79.1	3.68	8.36	1.11	0.113	0.159
105	1584.7	238.7	139.5	89.8	7.1	77.3	3.59	8.25	2.43	0.215	0.178
110	1385.0	203.7	120.2	82.8	6.2	74.5	3.46	8.03	4.82	0.439	0.197
115	1215.9	174.5	103.9	76.5	5.5	70.5	3.27	7.65	8.67	0.873	0.213
120	1072.3	150.1	90.2	70.7	4.9	64.9	3.01	7.11	14.3	1.60	0.225
125	949.3	129.5	78.5	65.3	4.3	57.8	2.68	6.37	21.6	2.67	0.230
130	842.9	112.0	68.5	60.5	3.8	49.4	2.29	5.49	30.5	4.02	0.226
135	750.8	97.2	60.0	56.0	3.3	40.4	1.87	4.52	40.3	5.51	0.214
140	670.6	84.6	52.7	51.9	2.9	31.4	1.46	3.54	50.4	6.92	0.194
145	600.6	73.7	46.3	48.0	2.6	23.1	1.07	2.62	60.3	7.96	0.168
150	539.1	64.4	40.8	44.5	2.3	15.7	0.725	1.79	69.9	8.28	0.137
155	484.0	56.2	35.9	41.3	2.0	9.18	0.425	1.06	79.6	7.36	0.100
160	432.3	48.5	31.4	38.2	1.8	3.44	0.159	0.397	90.9	4.16	0.0533
165	383.7	43.6	28.4	36.0	1.6	1.19	0.0549	0.138	96.0	2.22	0.0230
170	344.0	38.5	25.3	33.4	1.4	0.787	0.0364	0.0920	96.5	2.36	0.0158
175	309.7	34.0	22.5	31.0	1.3	0.612	0.0283	0.0719	95.8	3.23	0.0123
180	279.2	30.1	20.0	28.7	1.1	0.497	0.0230	0.0587	93.2	6.02	0.0102
185	252.1	26.9	17.9	26.9	1.0	0.385	0.0178	0.0457	84.4	15.0	0.00809
190	228.0	24.0	16.1	25.1	0.9	0.315	0.0146	0.0376	78.6	20.9	0.00674
195	207.2	21.4	14.4	23.3	0.8	0.270	0.0125	0.0324	75.7	23.9	0.00589
200	189.1	19.1	13.0	21.7	0.7	0.238	0.0110	0.0287	74.1	25.6	0.00526

Teststatistic for Higgs searches @ LEP, Tevatron & LHC

There are some differences in detail in the teststatistic used at LEP, Tevatron or LHC
(besides the preferred names "-2lnQ", "LLR" or "q_μ" in the publications)

μ : signal strenght = σ/σ_{SM} (μ=0: no signal, μ =1 nominal signal)

θ : nuisance parameters ~: average ^: profiling

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\tilde{\theta})}{\mathcal{L}(data\|0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|\hat{\mu},\hat{\theta})}$	yes $(0 \le \hat{\mu} \le \mu)$	frequentist