Direct and Indirect SM Higgs Search at LEP

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Overview

- **Result of the Electroweak fits**
  - Introduction
  - QED Finestructure Const.
  - EW Radiative Corrections
  - EW Fits
  - Results of the EW Fits
- **SM Higgs Direct Search**
  - SM Higgs Production and Decay
  - Analysis Strategies and Search Channels
  - Results of the four experiments at $\sqrt{s} = 189$ GeV
- **Combinations of the Results**
- **Combined Limit on SM Higgs at $\sqrt{s} = 189$ GeV**

Input parameters of SM

A-priori unknown parameters of the SM:

- $g_1,\ g_2,\ g_3$ **(coupling const. of the three gauge groups)**
- $\mu^2,\ \lambda$ **(Higgs potential parameters)**
- g_f **(Yukawa coupling between Higgs and fermions)**
- **elements of the Cabbibbo-Kobayashi-Maskawa mixing matrix**

Renormalizability of SM $\Rightarrow$ any observables can be calculated

However, it is better to change the parameters to:
$\alpha_{em}(m_Z^2),\ \alpha_s(m_Z^2),\ m_W,\ m_Z,\ m_H, m_{quarks}$

Since m_{quarks} (except m_t) are small and known $\Rightarrow$

There are only six parameters to measure:

$$\alpha_{em}(m_Z^2),\ \alpha_s(m_Z^2),\ m_W,\ m_Z,\ m_H, m_t$$

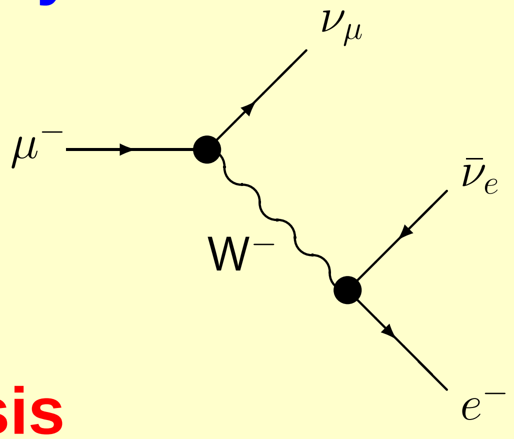
Replace $\mathrm{m_W}$ with the Fermi constant:

$$\frac{\mathsf{G_F}}{\sqrt{2}} = \frac{\pi\alpha(0)}{2} \cdot \frac{1}{m_W^2 \sin^2\theta_W} \cdot \frac{1}{1-\Delta\mathsf{r}}$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

$$\Delta\mathsf{r} = \Delta\alpha - \cot^2\theta_W \Delta\rho + \cdots$$

$\mathsf{G_F}$ precisely measured in muon decay

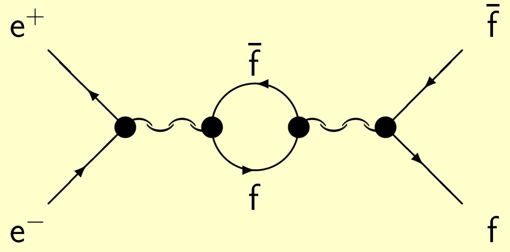


$\mathsf{G_F} =$ 1.16637(1) 10$\times^{-5}$ GeV^{-2}

Error on $\mathsf{G_F}$ negligible for SM analysis

QED constant α

Fermion loops:



$$\alpha(0) = \frac{1}{137.0359895(61)} \longrightarrow$$

$$\alpha(m_Z^2) = \frac{\alpha(0)}{1-\Delta\alpha} = \frac{1}{128.896 \pm 0.090}$$

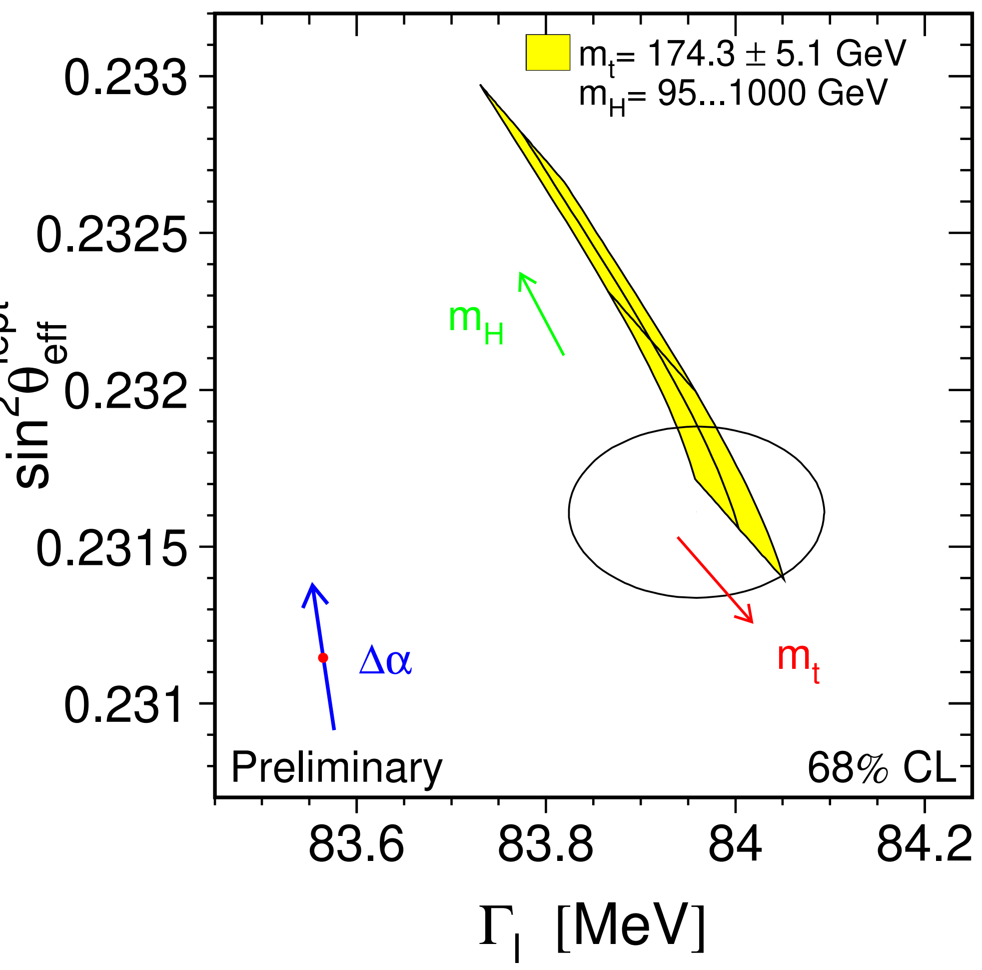
Two possibilities:

- **Take measurement results on $\sigma_{had} \Rightarrow$ Large error on $\alpha(m_Z^2)$**
- **Take theory with less error**

We use the experimental results.

Need σ_{had} measurement at $\sqrt{s}$= 1-7 GeV. (BES)

Running of α is not sufficient alone to describe measurements



$\Rightarrow$ **Weak corrections (m_t, m_H) are necessary**

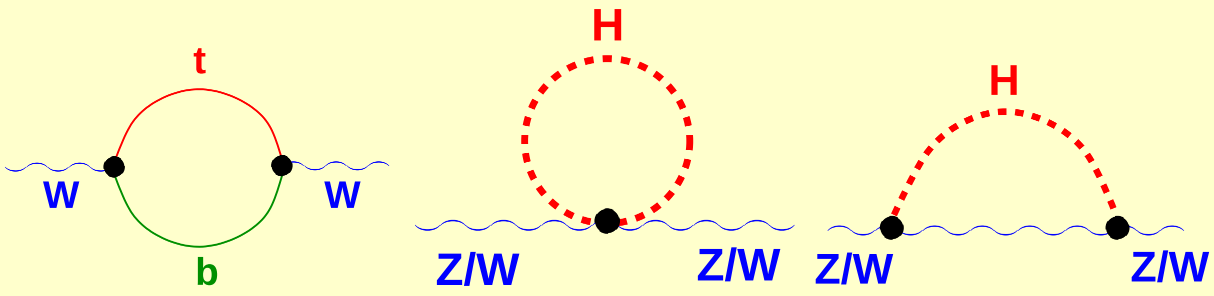
Electroweak couplings of the weak current:

$$g_{Vf} = T_f^3 - 2q_f \sin^2\theta_W \rightarrow$$
$$\rightarrow \sqrt{\rho}\cdot(T_f^3 - 2q_f \sin^2\bar{\theta}_W)$$
$$g_{Af} = T^3 \rightarrow \sqrt{\rho}\cdot T^3$$

Electroweak radiative corrections:

$$\rho = \frac{1}{1-\Delta\rho}, \qquad \frac{\sin^2\bar{\theta}_W}{\sin^2\theta_W} = 1 + \cot^2\theta_W \Delta\rho + \cdots$$

Dependence of EW radiative corrections:



$\propto m_t^2$ $\qquad\qquad$ $\propto \log \frac{m_H}{m_W}$

Higher sensitivity to m_t than m_H

Precise EW measurements are sensitive to the EW radiative corrections

Predict $\mathrm{m_W}$, $\mathrm{m_t}$, $\mathrm{m_H}$

Testing the Standard Model

Giving constraints on SM parameters

Programs to do the fits:

- **TOPAZ0**
- **ZFITTER**

Implemented recent theoretical calculations:

- **QED radiator to** $\mathcal{O}(\alpha^3)$
- **Four loop QCD effects**
- **Nonfactorisable QCD/QED corrections**
- **Two-loop** $\mathcal{O}(\alpha^2 m_t^2/m_W^2)$ **corrections**

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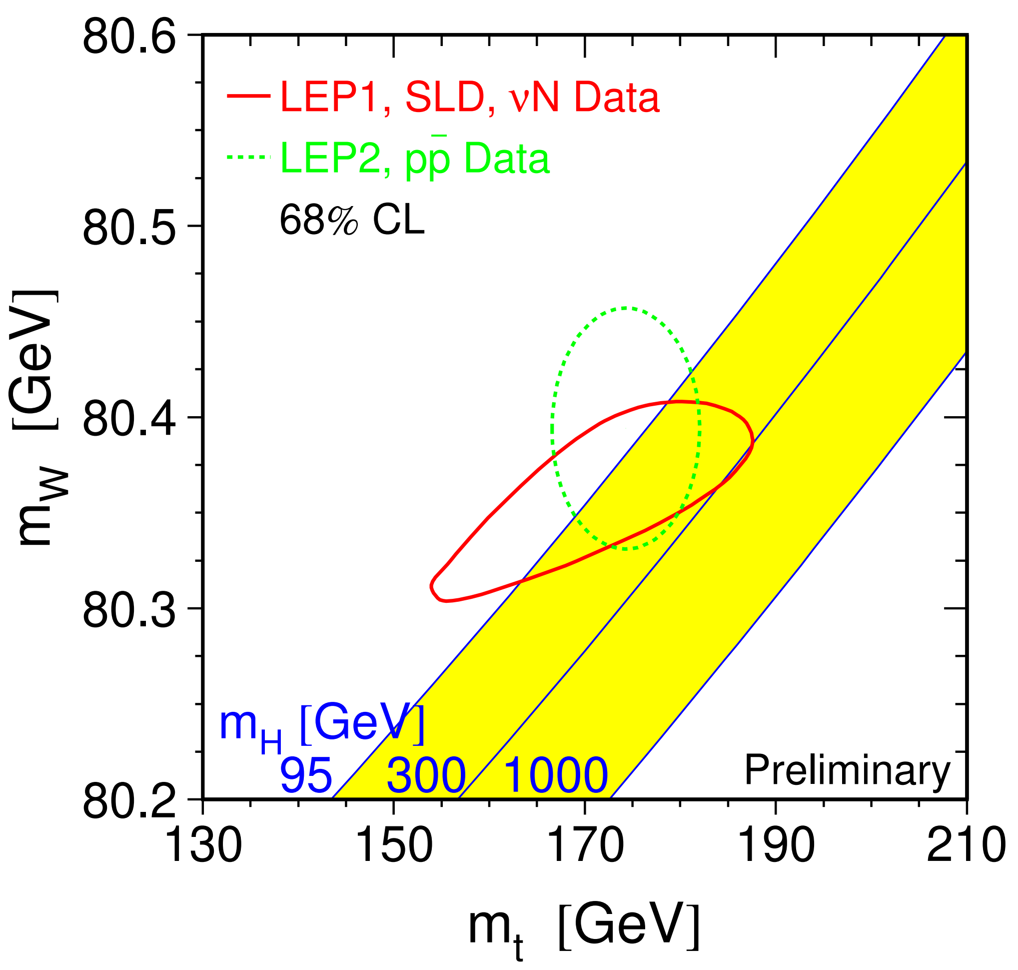
Result of the fits

SM Predictions for m_W and m_t are in good agreement with the measurements



Result of the fits

Standard Model analysis results:

Include the direct measurement results for m_W and m_t

With $\Delta\alpha^{(5)}_{had}$ = 0.02804±0.00065:

- χ^2/dof = 21.6/15 (12 %)
- m_t = 174.3± 5.1 GeV
- $\log_{10} m_H = 1.96^{+0.27}_{-0.29}$ ($m_H = 92^{+78}_{-45}$ GeV)
- $\alpha_s(m_Z^2)$ = 0.119±0.003

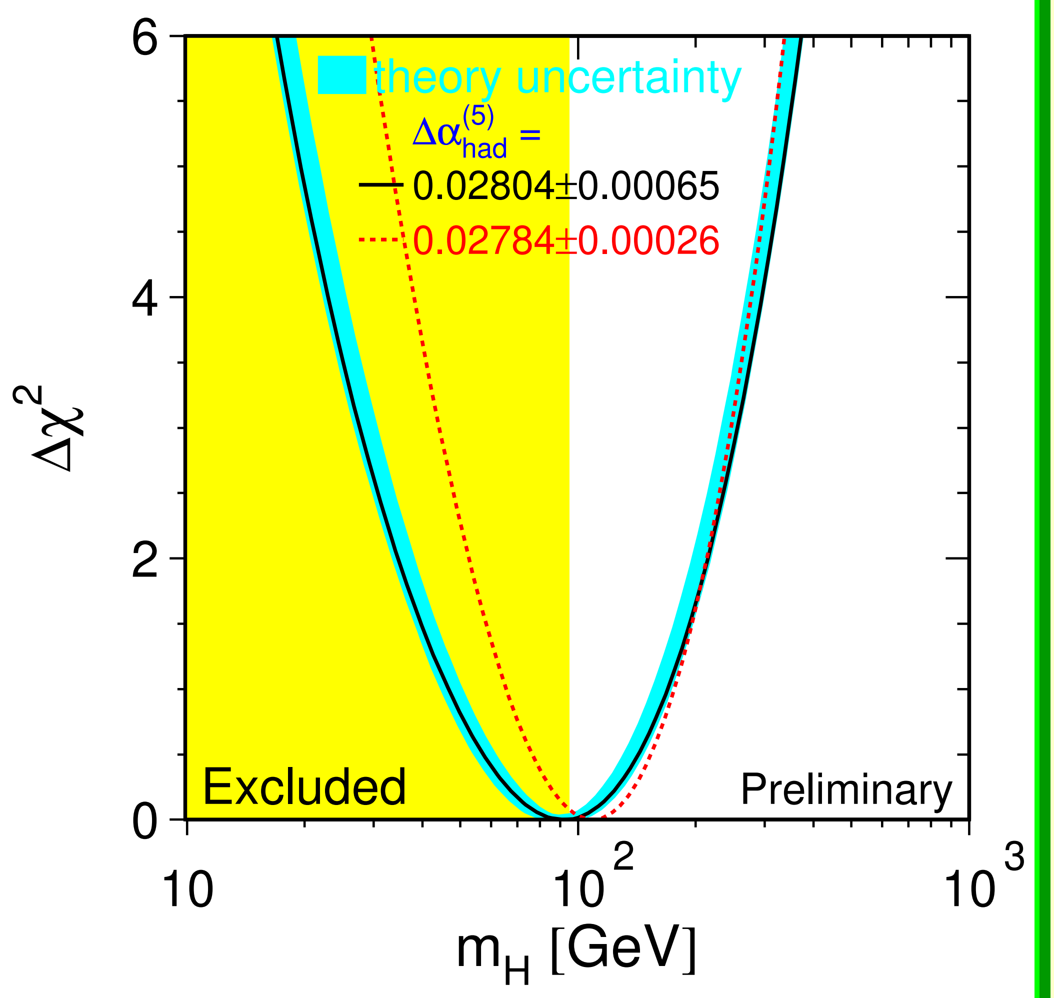
Correlation between m_H and $\alpha(m_Z^2)$: 50%

With $\Delta\alpha^{(5)}_{had}$ = 0.02784±0.00026:

$\log_{10} m_H = 2.04^{+0.21}_{-0.22}$ ($m_H = 109^{+67}_{-44}$ GeV)

Correlation between m_H and $\alpha(m_Z^2)$: 21%

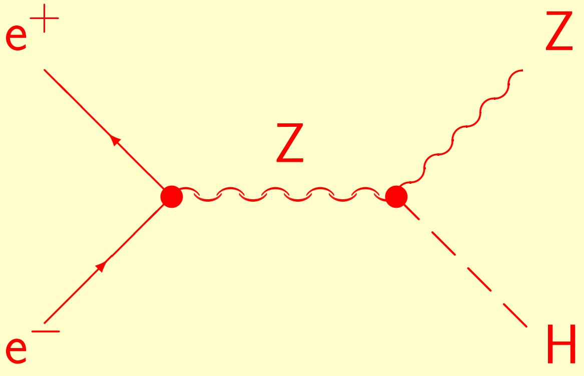
Constraint on m_H

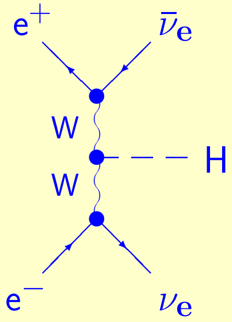


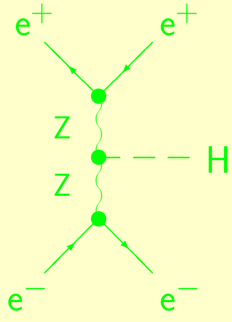
One-sided 95% CL upper limit:

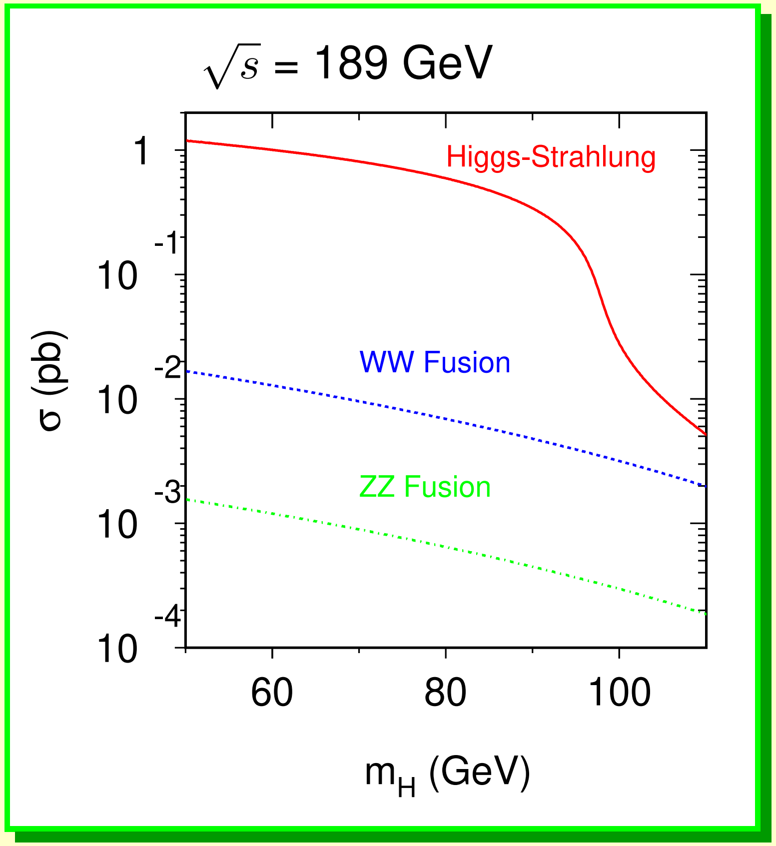
$m_H < 245$ GeV

SM Higgs Production at LEP









⇒ LEP searches for Higgs-Strahlung

Decay Channels:

$H \to b\bar{b} \quad \approx 86\%$

$H \to \tau^+\tau^- \quad \approx 8\%$

Smaller contributions from

$H \to c\bar{c}$, gg

Background:

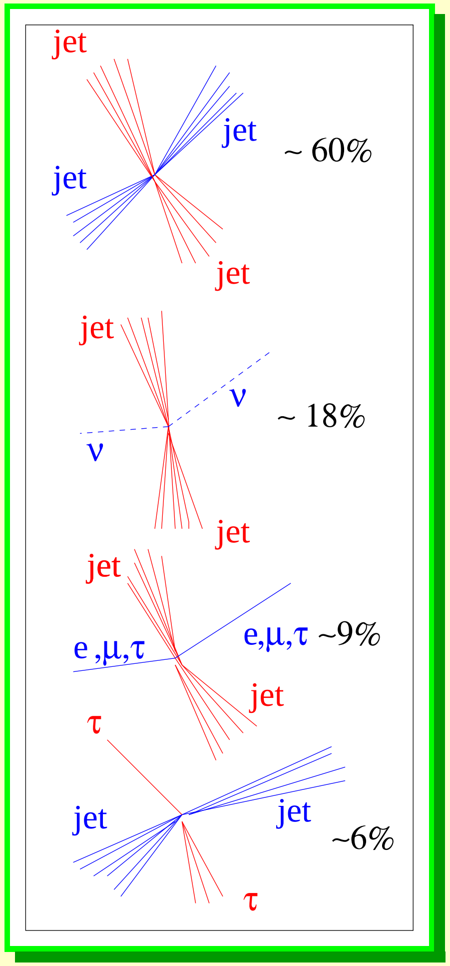
$ZZ \to q\bar{q},\ l\bar{l},\ \nu\bar{\nu}$

$WW \to q\bar{q},\ l\bar{l},\ \nu\bar{\nu}$

$W\bar{\nu}e^- \to q\bar{q}\ \bar{\nu}e^-$

$q\bar{q} \to q\bar{q}gg$

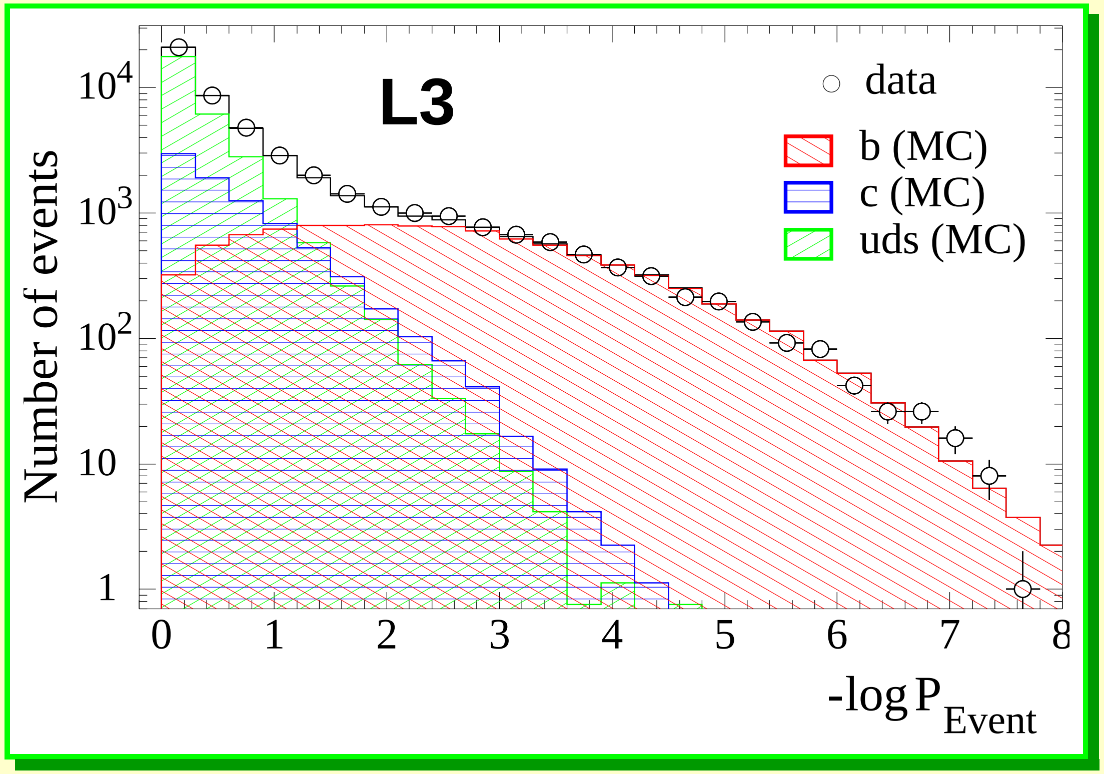
Event Topologies:



Analysis Strategies

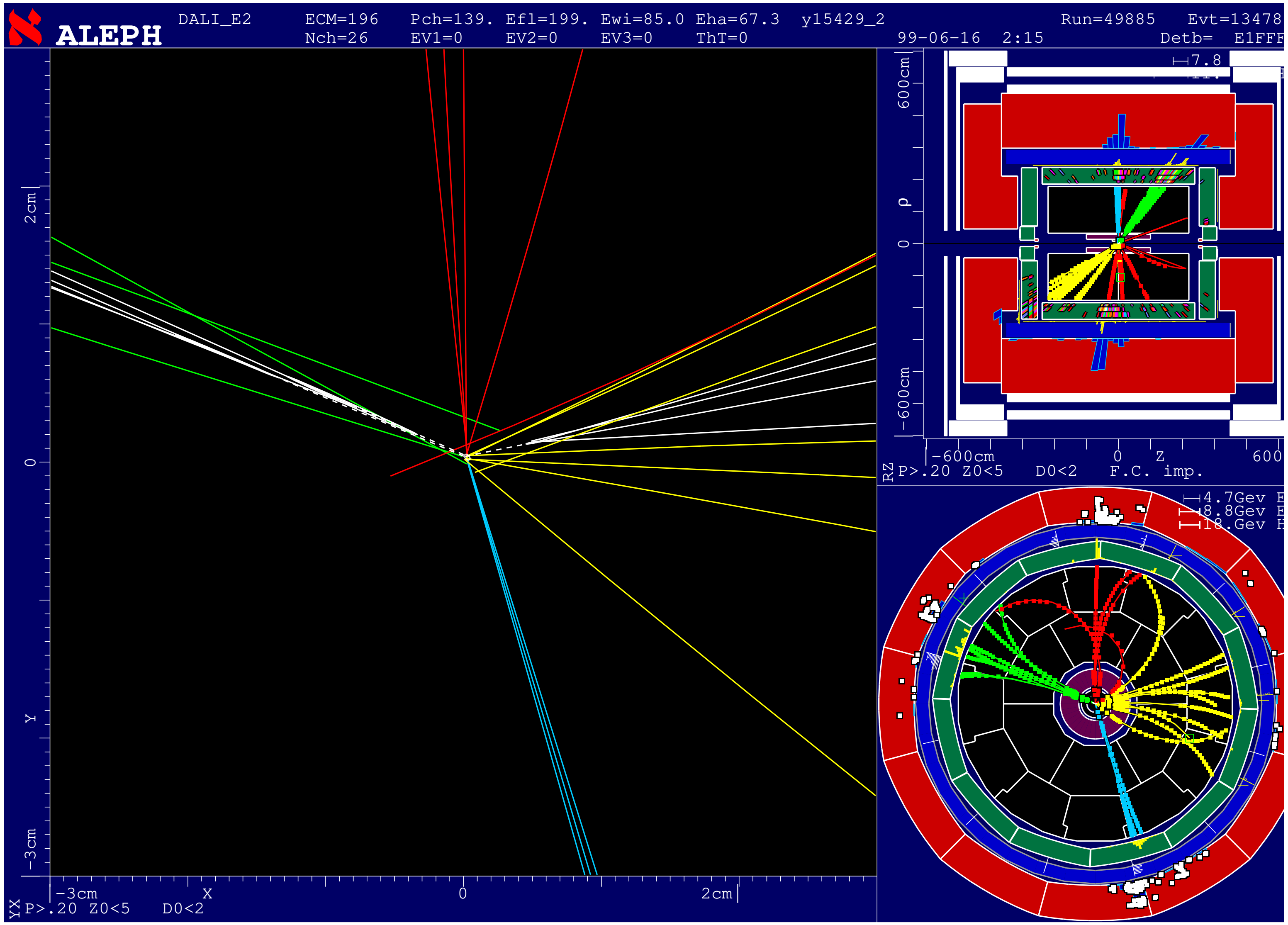
- Mass independent selection of high multiplicity events
- Use of Kinematic fit
- Use of b-tagging
- Final discriminant is constructed via Neural Network or Likelihood

Power of b-tagging

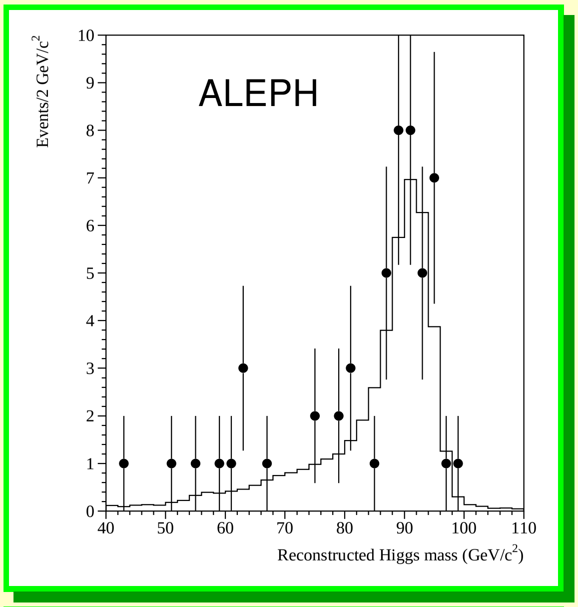


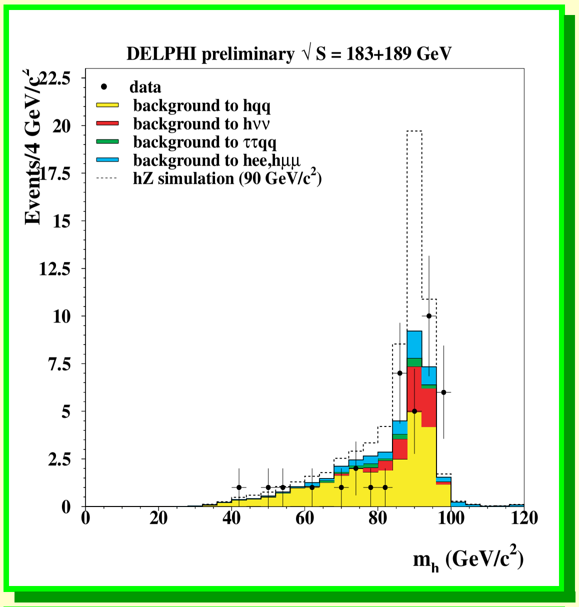
75 % efficiency / 80 % purity ($Z \to b\bar{b}$ at $\sqrt{s} = 91$ GeV)

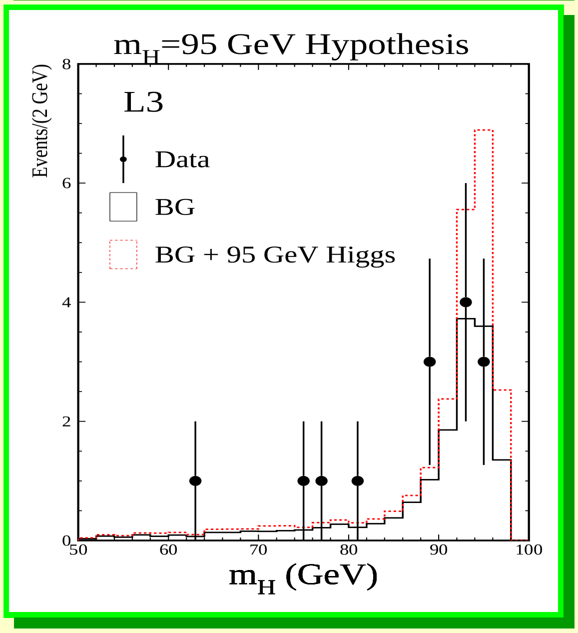
SM Higgs Direct Search

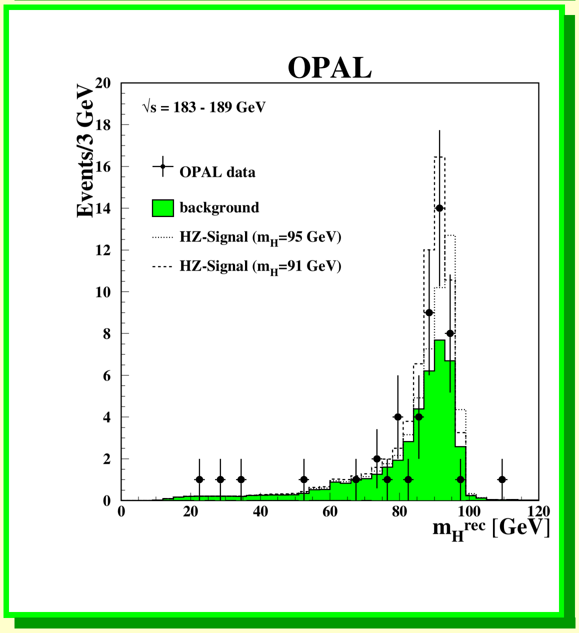


SM Higgs Mass Distributions at $\sqrt{s} = 189$ GeV









Results of the four experiments at $\sqrt{s} = 189$ GeV

The existence of the SM Higgs boson is excluded by the individual experiments at 95% CL up to:

ALEPH	$m_H >$ **92.9 GeV**
DELPHI	$m_H >$ **95.2 GeV**
L3	$m_H >$ **95.3 GeV**
OPAL	$m_H >$ **91.0 GeV**

Combination of the Results

Aim:

Better result (limit) is expected since the $\int \mathcal{L}$ is higher

Problems:

- **Many search channels**
- **Various analysis procedures**
- **Large number of different center-of-mass energies**

LEP Higgs WG has considered several statistical procedures
(tested by “gedanken experiments”)

Inputs:

- **Reconstructed Higgs Boson mass**
- **Or any other variables with discriminating power**

Confidence Limits:

- $CL_{s+b}(m_H) = P(X_{s+b}(m_H) \leq X_{obs})$
- $CL_b(m_H) = P(X_b(m_H) \leq X_{obs})$
- $CL_s = \frac{CL_{s+b}}{CL_b}$ (A,B,C)

95% CL lower limit on Higgs:

$$CL_s(\min m_H) = 0.05$$

Two methods applied to $\sqrt{s} = 189$ GeV data

They differ in definitions of test statistics $X(m_H)$

Methods A & B:

Use the Likelihood function for the *signal + background* hypothesis

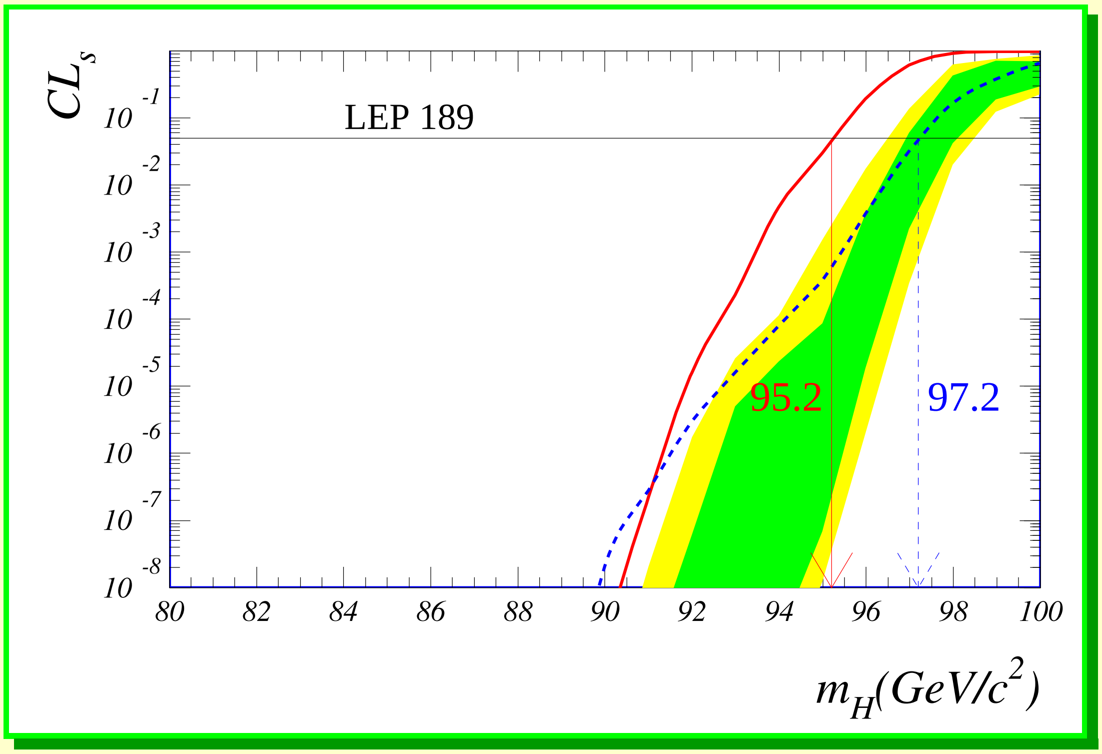
Method A: $X(m_H) = \frac{\mathcal{L}(s+b(m_H))}{\mathcal{L}(b(m_H))}$

Method B: $X(m_H) = \frac{\int_{s(m_H)}^{\infty} \mathcal{L}(x)dx}{\int_0^{\infty} \mathcal{L}(x)dx}$ Bayesian probability with a flat prior distribution

Methods require as input:

- **Integrated signal and background rates**
- **probability distributions for signal and background**
- m_{ij} **(or the other disc. var.) for every candidate j in ch. i**

Expected & Observed CL



95% CL (GeV)	Statistical Method A	B
Expected	97.2	97.4
Observed	95.2	95.6

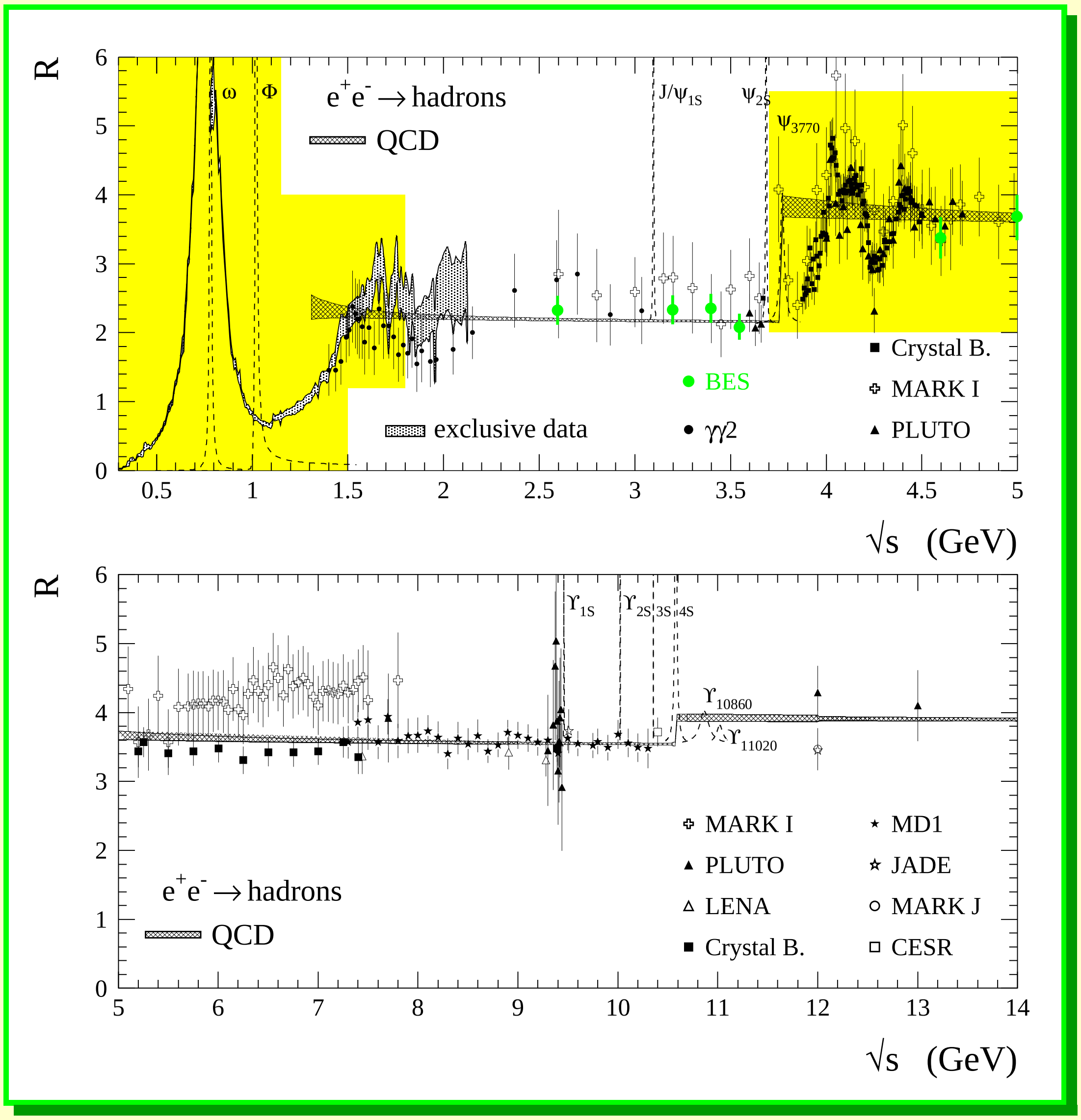
$\sqrt{s} = 189$ GeV $\int \mathcal{L} = 683$ pb^{-1}

Combined Limit on SM Higgs at $\sqrt{s} = 189$ GeV

The existence of the SM Higgs boson is excluded by the combination of the four LEP experiments at 95% CL in the mass region:

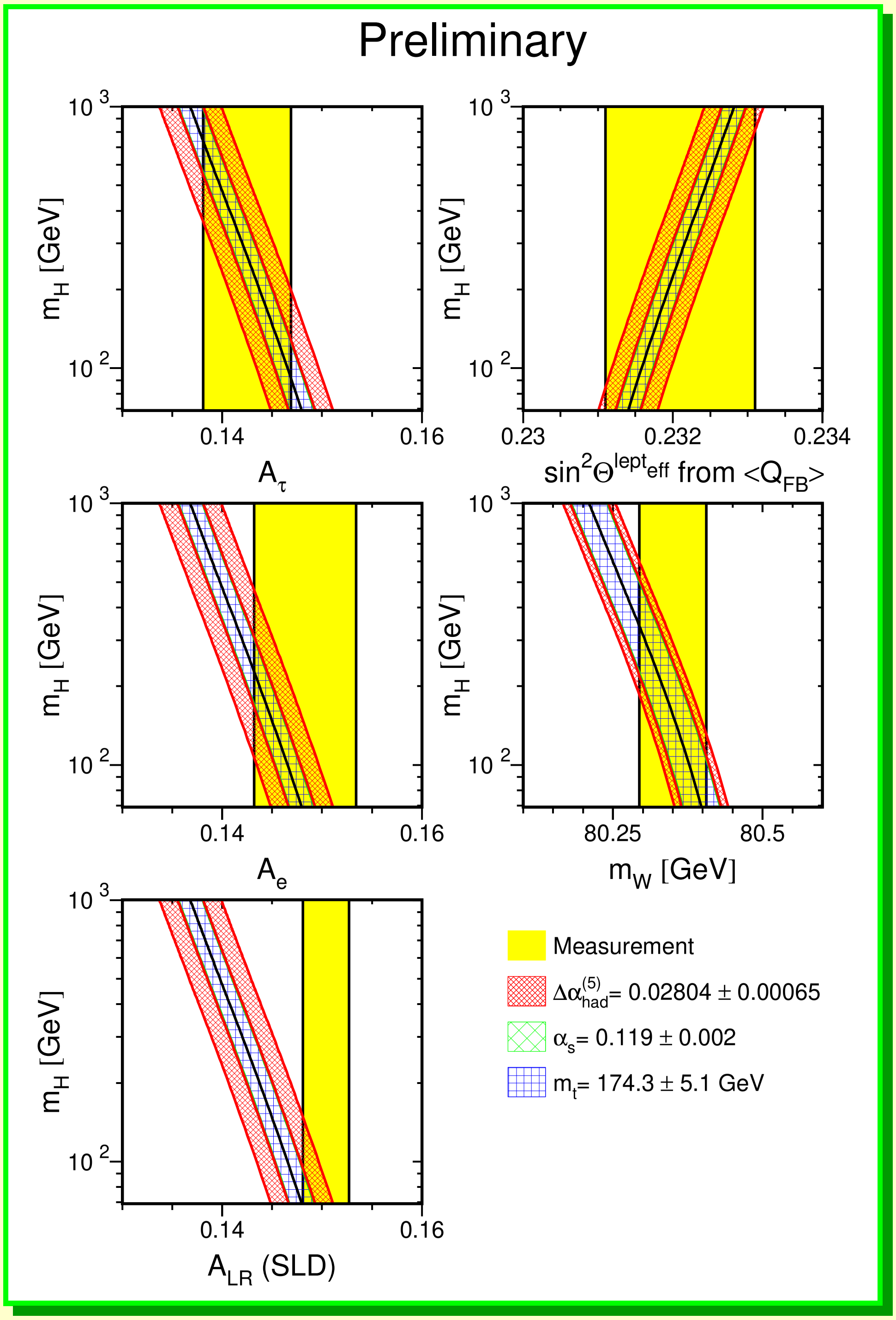
$$m_H \leq 95.2\ \mathrm{GeV}/c^2$$

Appendix

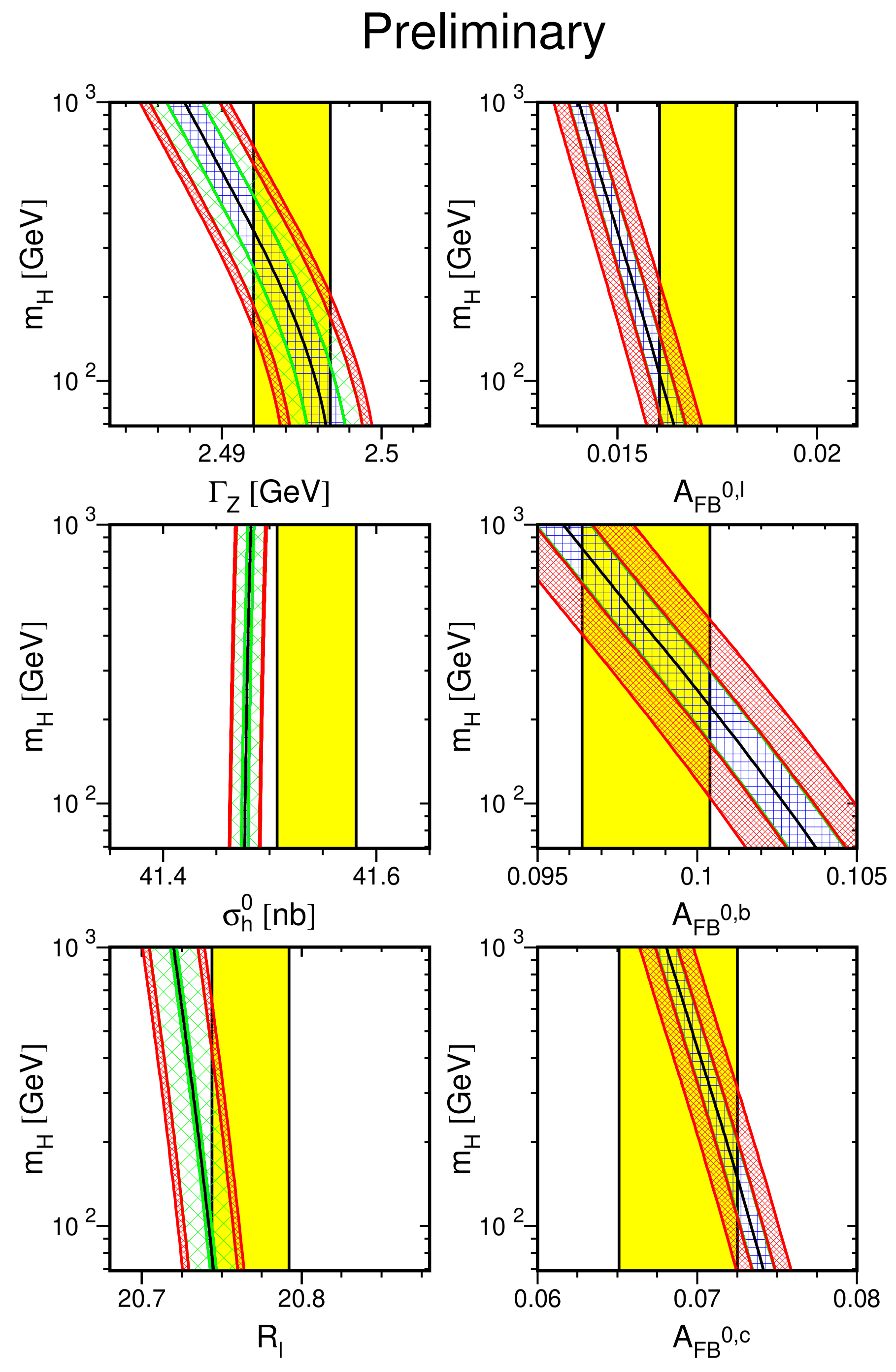


R
e⁺e⁻ → hadrons
QCD
exclusive data
ω
Φ
J/ψ1S
ψ2S
ψ3770
Crystal B.
BES
MARK I
γγ2
PLUTO
√s (GeV)
R
Υ1S
Υ2S 3S 4S
Υ10860
Υ11020
MARK I
MD1
PLUTO
JADE
LENA
MARK J
Crystal B.
CESR
e⁺e⁻ → hadrons
QCD
√s (GeV)

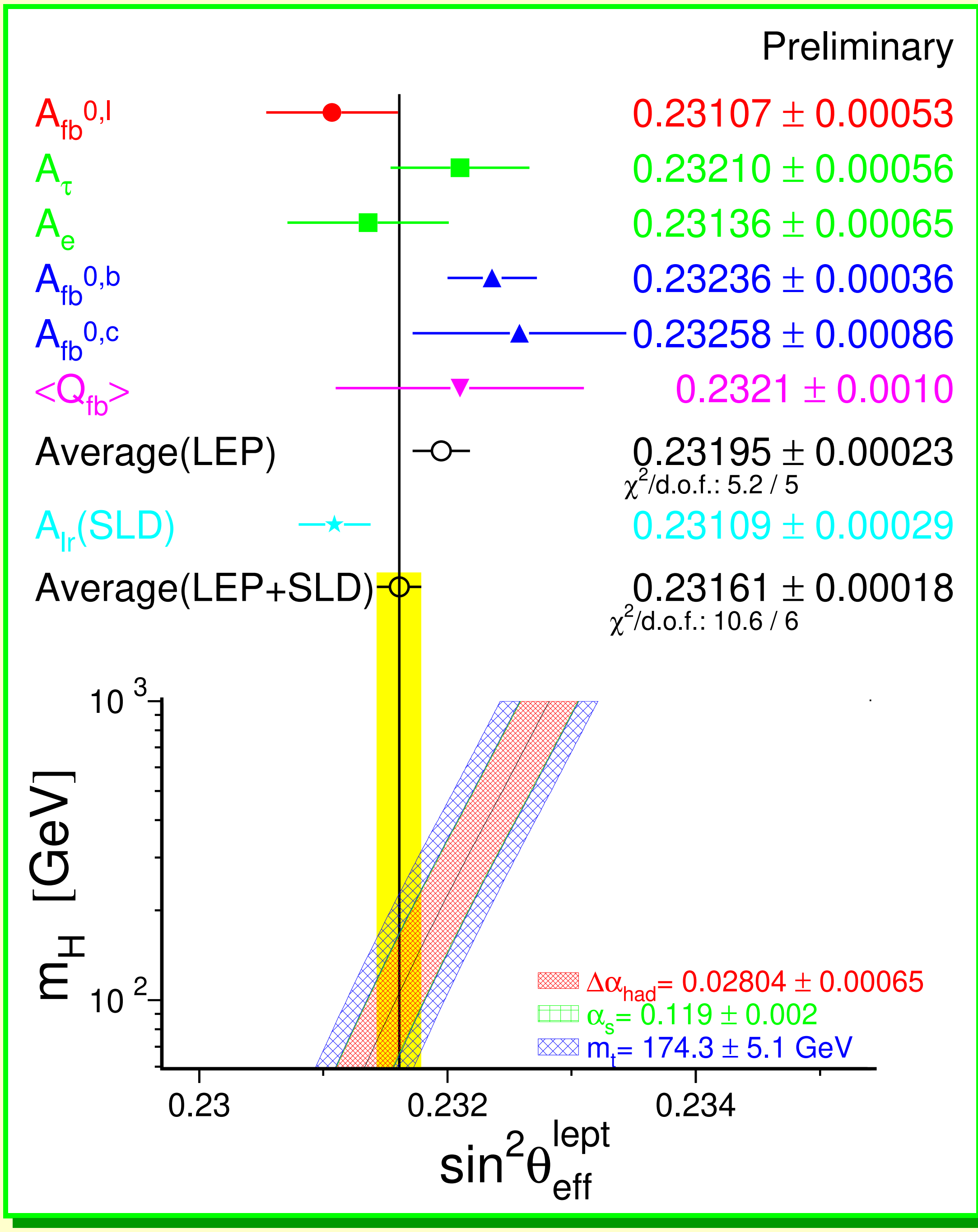
Higgs sensitivity



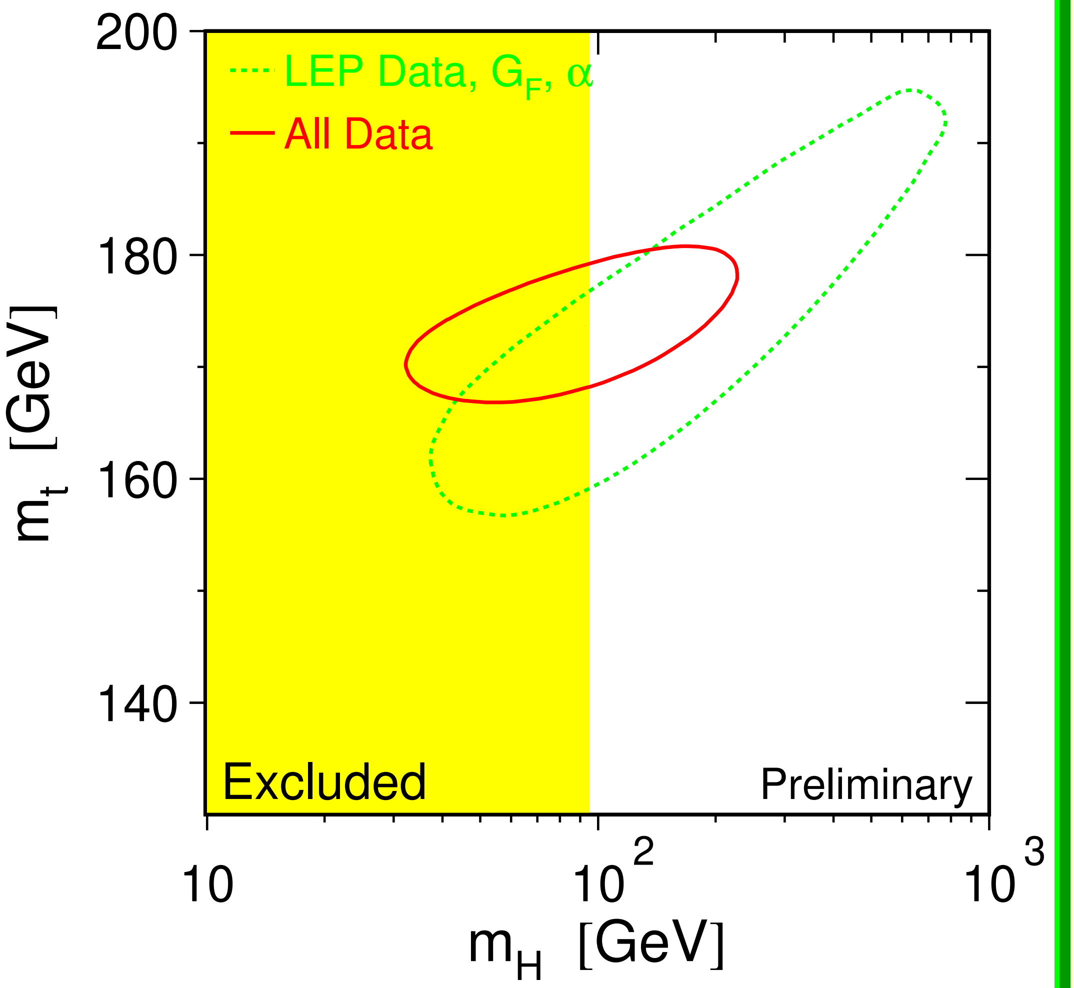
Higgs sensitivity



Measurements of $\sin^2\vartheta$ and its effect on m_H



Top and Higgs



The **HZ** $\rightarrow$ $b\bar{b}q\bar{q}$ Channel

Signature:

- 4 Jet structure
- high multiplicity
- full energy in the detector
- balanced in momentum

Results at $\sqrt{s} = 189$ GeV:

	A	D	L	O
$\mathcal{L}(\mathrm{pb}^{-1})$	176.2	158.0	176.4	185.0
η_{Signal} (%)	8.5*	44	62	47
Backgr.	22	22	270	20
Data	28	24	289	24

*: Normalised expected signal events

Relevant Backgrounds:

$WW \rightarrow q\bar{q}q\bar{q}$

$ZZ \rightarrow q\bar{q}q\bar{q}$

$q\bar{q}$

The **HZ** $\rightarrow$ $b\bar{b}\nu\bar{\nu}$ Channel

Signature:

- 2 acoplanar jets
- missing transverse momentum
- high multiplicity

Results at $\sqrt{s} = 189$ GeV:

	A	D	L	O
η_{Signal} (%)	2.0*	34	62	35.4
Backgr.	3.1	6	116	6.9
Data	5	4	109	10

*: Normalised expected signal events

Relevant Backgrounds:

$WW \rightarrow q\bar{q}\tau\nu$

$ZZ \rightarrow q\bar{q}\nu\bar{\nu}$

$We\nu$

$q\bar{q}(\gamma)$

The **HZ** $\rightarrow$ $\mathrm{b\bar{b}l^+l^-}(\tau^+\tau^-\mathrm{q\bar{q}})$ Channels

Signature:

- 2 jets + 2 leptons

Backgrounds:

$\mathrm{ZZ} \rightarrow \mathrm{q\bar{q}l\bar{l}}$
$\mathrm{WW} \rightarrow \mathrm{q\bar{q}l}\nu$

*: Normalised expected signal events
†: All three channels are summed up

Results at $\sqrt{s} = 189$ GeV:

$H\tau\tau$ $(\tau\tau q\bar{q})$

	A	D	L	O
η_{Signal} (%)	1.5*†	18	30	34.3
Backgr.	14.1†	0.76	17.1	4.0
Data	14†	0	12	3

$H\mu\mu$

	A	D	L	O
η_{Signal} (%)	1.5*†	61	57	64.9
Backgr.	14.1†	1.69	5.5	2.1
Data	14†	2	5	1

Hee

	A	D	L	O
η_{Signal} (%)	1.5*†	50.4	77	55
Backgr.	14.1†	2.58	13.2	2.6
Data	14†	1	15	3

Likelihood function for the *signal + background* hypothesis of Method A & B:

$$\mathcal{L}(x) = \prod_{i=1}^{N} \frac{\exp\left[-\left(x\frac{s_i(m_H)}{s(m_H)} + b_i\right)\right]\left(x\frac{s_i(m_H)}{s(m_H)} + b_i\right)^{n_i}}{n_i!} \times \prod_{i=1}^{N} \frac{x\frac{s_i(m_H)}{s(m_H)} S_i(m_H, m_{ij}) + b_i B_i(m_{ij})}{x\frac{s_i(m_H)}{s(m_H)} + b_i}$$

N are the channels (different CM, different collaborations)

n_i is the number of candidates in channel i

m_{ij} is the m of candidate j in channel i

$s_i(m_H)$, b_i are the integrated signal and background in channel i

$s(m_H) = \sum_{i=1}^{N} s_i(m_H)$, $b = \sum_{i=1}^{N} b_i$

$S_i(m_H, m)$, $B_i(m)$ are the probability distributions for signal and background

x =0: background only, $=s(m_H)$: signal+background

Method C: **Fractional event counting. A weight w_{ij} is assigned to each selected candidate j in channel i.**

$$X(m_H) = \sum_{i=1}^{N} \sum_{j=1}^{n_i} w_{ij}(m_H)$$

Weight function for Method C:

$$w_{ij} = K(m_H) \frac{s_i \cdot S_i(m_H, m_{ij})}{\frac{1}{2} s_i \cdot S_i(m_H, m_{ij}) + b_i \cdot B_i(m_{ij})}$$

$K(m_H)$ is an overall normalisation factor
m_{ij} is the m of candidate j in channel i
$s_i(m_H)$, b_i are the integrated signal and background in channel i
$s(m_H) = \sum_{i=1}^{N} s_i(m_H)$, $b = \sum_{i=1}^{N} b_i$
$S_i(m_H, m)$, $B_i(m)$ are the probability distributions for signal and background.